Diesel Mechanics

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Global Media
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First Edition, 2007

ISBN 978 81 904575 6 9

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Published by:

Global Media
1819, Bhagirath Palace,
Chandni Chowk, Delhi-110 006
Email: globalmedia@dkpd.com

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Diesel locomotive

Diesel locomotives became the dominant type of locomotive in rail transport in the mid 20th century in much of the world. Powered by diesel engines, they use a variety of transmissions to convey power to the wheels. Diesel locomotives, in contrast to electric locomotives, do not require catenary installations to run. Therefore, they offer more flexibility in various types of service and are generally predominant in countries which, for historical or economical reasons, have few electrified lines. Since the 1950s, however, they have been superseded by electric locomotives in terms of power, maximum speed, tractive effort, and acceleration.

History

Rudolf Diesel had suggested that his engine could be employed in railroad service, and in 1909 helped to construct an experimental locomotive.

In 1918 diesel electric switching locomotives were put in service in the United States. Sixteen years later, mainline engines began to be produced, at first for passenger service. Custom units were produced at at first for the Chicago, Burlington and Quincy Railroad's Pioneer Zephyr and as a single unit for the Baltimore and Ohio Railroad. Mass production of passenger and freight units soon followed. By 1960, diesel-electrics had displaced steam locomotives on every Class I railroad in the United States of America.

United Kingdom

In the 1970s British Rail developed a high-speed diesel-electric train called the High Speed Train or HST. This train consists of two Class 43 locomotives (also known as power cars), one at each end, and a number of "Mark 3" carriages (usually 8). A complete HST set was originally designated as a Class 253 or 254 diesel multiple unit (DMU), but due to the frequent exchanges between sets the power cars were reclassified as locomotives and given class number 43. The unpowered carriages were simultaneously reclassified as individual coaches; the number of a DMU set should identify all its associated carriages as well.

The HST holds the world speed record for diesel traction, having reached a speed of 148 mph, although the operating speed in service is 125 mph (200 km/h), hence the name "Inter-City 125".

Transmission types

Unlike steam engines, diesel engines require a transmission to power the wheels. The engine must continue to idle when the locomotive is stopped.

Diesel-mechanical

A British Rail Class 03 diesel-mechanical shunter with a jackshaft under the cab.

The simplest form of transmission is by means of a gearbox, in the same way as on road vehicles. Diesel trains or locomotives that use this are called diesel-mechanical and began to appear after World War I.

It has been found impractical to inexpensively build a gearbox which can cope with a power output of more than 400 horsepower (300 kW) without failure, despite a number of attempts to do so. Therefore this type of transmission is only suitable for low-powered shunting locomotives, or lightweight multiple units or railcars.

For more powerful locomotives, other types of transmission have to be used.

Diesel-electric

EMD SD70 series diesel-electric locomotives of the Union Pacific refueling at Dunsmuir, California.

The most common form of transmission is electric; a locomotive using electric transmission is known as a diesel-electric locomotive. With this system, the diesel engine drives a generator or alternator; the electrical power produced then drives the wheels using electric motors. This is effectively an electric locomotive with its own generating station.

For the first decades the motors were direct current. More recently alternating current has come to be preferred. In either case, a common option is the use of dynamic braking, in which the motors are switched to perform as generators, thus converting the motion of the locomotive into electrical energy, which is then dissipated through heating elements usually mounted on the top of the locomotive. Dynamic braking reduces brake usage in mountainous areas, though it is ineffective at low speeds.

Electro-diesel

Electro-diesel locomotive

These are special locomotives that can either operate as an electric locomotive or a diesel locomotive. Dual-mode diesel-electric/third-rail locomotives are operated by the Long Island Rail Road and Metro-North Railroad between non-electrified territory and New York City because of a local law banning diesel-powered locomotives in Manhattan tunnels. For the same reason, Amtrak operates a fleet of dual-mode locomotives in the New York area. British Rail operated dual diesel-electric/electric locomotives designed to run primarily as electric locomotives. This allowed railway yards to remain un-electrified as the third-rail power system is extremely hazardous in a yard area.

Diesel-hydraulic

DB class V200.

Alternatively, diesel-hydraulic locomotives use hydraulic transmission to convey the power from the diesel engine to the wheels. On this type of locomotive, the power is transmitted to the wheels by means of a device called a torque converter. A torque converter consists of three main parts, two of which rotate, and one which is fixed. All three main parts are sealed in a housing filled with oil.

The inner rotating part of a torque converter is called a *centrifugal pump* (or impeller), the outer part is called a *turbine wheel* (or driven wheel), and between them is a fixed guide wheel. All of these parts have specially shaped blades to control the flow of oil.

The centrifugal pump is connected directly to the diesel engine, and the turbine wheel is connected to an axle, which drives the wheels.

As the diesel engine rotates the centrifugal pump, oil is forced outwards at high pressure. The oil is forced through the blades of the fixed guide wheel and then through the blades of the turbine wheel, which causes it to rotate and thus turn the axle and the wheels. The oil is then pumped around the circuit again and again.

The disposition of the guide vanes allows the torque converter to act as a "gearbox" with continuously variable ratio. If the output shaft is loaded so as to reduce its rotational speed, the torque applied to the shaft increases, so the power transmitted by the torque converter remains more or less constant.

However, the range of variability is not sufficient to match engine speed to load speed over the entire speed range of a locomotive, so some additional method is required to give sufficient range. One method is to follow the torque converter with a mechanical gearbox which switches ratios automatically, similar to an automatic transmission on a car. Another method is to provide several torque converters each with a range of variability covering part of the total required; all the torque converters are mechanically connected all the time, and the appropriate one for the speed range required is selected by filling it with oil and draining the others. The filling and draining is carried out with the transmission under load, and results in very smooth range changes with no break in the transmitted power.

Diesel-hydraulic multiple units, a less arduous duty, often use a simplification of this system, with a torque converter for the lower speed ranges and a fluid coupling for the high speed range. A fluid coupling is similar to a torque converter but the ratio of input to output speed is fixed; loading the output shaft results not in torque multiplication and constant power throughput but in reduction of the input speed with consequent lower power throughput. (In car terms, the fluid coupling provides top gear and the torque converter provides all the lower gears.) The result is that the power available at the rail is reduced when operating in the lower speed part of the fluid coupling range, but the less arduous duty of a passenger multiple unit compared to a locomotive makes this an acceptable tradeoff for reduced mechanical complexity.

Diesel-hydraulic locomotives are slightly more efficient than diesel-electrics, but were found in many countries to be mechanically more complicated and more likely to break down. In Germany, however, diesel-hydraulic systems achieved extremely high reliability in operation. Persistent argument continues over the relative reliability of hydraulic systems, with continuing questions over whether data was manipulated politically to favour local suppliers over German ones. In the US and Canada, they are now greatly outnumbered by diesel-electric locomotives, while they remain dominant in some European countries. The most famous diesel-hydraulic locomotive is the German V200 which were built from 1953 in a total number of 136. The only diesel-electric locomotives of the *Deutsche Bundesbahn* were BR 288 (V 188), of which 12 were built in 1939 by the DRG.

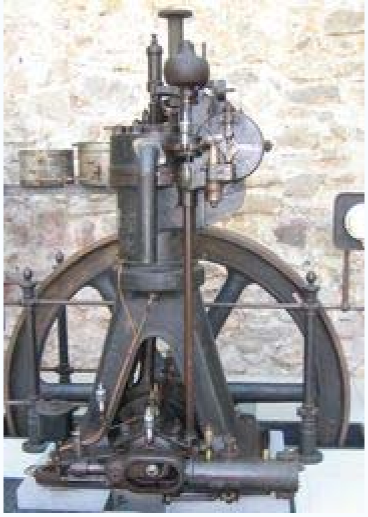
The high reliability of the German locomotives was paralleled by higher reliability of non-German locomotives built with German-made parts compared to that of the same designs built using parts made locally to German patterns under licence. Much of the unreliability experienced outside Germany was due to poor quality control in the local manufacture of engines and transmissions. Another contributing factor was poor maintenance due to staff accustomed to steam locomotives now working on unfamiliar and much more complex designs in unsuitable conditions, and failing to follow the unit-replacement maintenance methods which were part of the German success. It is notable that diesel-hydraulic multiple units, with the advantages of modern manufacturing techniques and improved maintenance procedures, are now extremely successful in widespread use, achieving excellent reliability.

In the 1960s, more than 15 diesel-hydraulic locomotives were purchased by the Denver & Rio Grande and Southern Pacific Railroads on a trial basis from the Kraus-Maffei company. Only the outer shell of one of these (converted into a camera car by SP in the 1970s) exists today, the others having all been scrapped.

Multiple unit operation

When mainline diesels were mass produced in the United States, they were initially sold as multiple unit sets. The engines and traction motors of the day were not capable of the power output needed to pull an entire train with a single unit. These units were controlled through the same type of multiple unit system already in use for electric locomotives. The "American Association of Railroads" standard for multiple-unit control remains the basis for US operation. The Kraus-Maffei diesel-hydraulic units were also equipped with this system.

Diesel engine



A Diesel engine built by MAN AG in 1906

PATENT-URKUNDE

KAISERLICHES PATENTAMT

Rudolf Diesel's 1893 patent on his engine design

The **diesel engine** is a type of internal combustion engine; more specifically, it is a **compression ignition engine**, in which the fuel is ignited solely by the high temperature created by compression of the air-fuel mixture, rather than by a separate source of ignition, such as a spark plug, as is the case in the gasoline engine.

The engine operates using the diesel cycle.

The engine is named after German engineer Rudolf Diesel, who invented it in 1892 based on the hot bulb engine and received the patent on February 23, 1893. Diesel intended the engine to use a variety of fuels including coal dust. He demonstrated it in the 1900 *Exposition Universelle* (World's Fair) using peanut oil (see biodiesel).

Early history timeline

- 1862 - Nicolaus Otto develops his coal gas engine, similar to a modern gasoline engine.
- 1891 - Herbert Akroyd-Stuart, of Bletchley perfects his oil engine, and leases rights to Hornsby of England to build engines. They build the first cold start, compression ignition engines
- 1892 - Hornsby engine No. 101 is built and installed in a waterworks. It is now in the MAN truck museum in Northern England.
- 1892 - Rudolf Diesel develops his Carnot heat engine type motor which burnt powdered coal dust. He is employed by refrigeration genius Carl von Linde, then Munich iron manfacturer MAN AG and later by the Sulzer engine company of Switzerland. He borrows ideas from them and leaves a legacy with all firms.
- 1892 - John Froelich builds his oil engine powered farm tractor.
- 1894 - Witte, Reid, and Fairbanks start building oil engines with a variety of ignition systems.
- 1896 - Hornsby builds diesel tractors and railway engines.
- 1897 - Winton produces and drives the first US built gas automobile; he later builds diesel plants.
- 1897 - Mirrlees, Watson & Yaryan build the first British diesel engine under license from Rudolf Diesel. This is now displayed in the Science Museum at South Kensington, London.
- 1898 - Busch installs a Rudolf Diesel type engine in his brewery in St. Louis. It is the first in the United States. Rudolf Diesel perfects his compression start engine, patents and licences it. This engine, pictured above, is in a German museum.

- 1899 - Diesel licenses his engine to builders Burmeister & Wain, Krupp and Sulzer who become famous builders.
- 1902 - F. Rundlof invents the two stroke crankcase, scavanged hot bulb engine.
- 1903 Ship Gjoa transits the ice filled, Northwest Passage, aided with a Dan kerosene engine.
- 1904 - French build the first diesel submarine, the Z,
- 1908 - Bolinder/Munktell started building two stroke hot-bulb engines.
- 1912 - First diesel ship MS Selandia is built. SS Fram, polar explorer Amundsen’s flagship, converted to a AB Atlas diesel.
- 1913 - Fairbanks Morse starts building its Y model semi-Diesel. US Navy submarines use NELSECO units.
- 1914 - German U-Boats are powered by MAN diesels. War service proves engine's reliability.
- 1920s - Fishing fleets convert to oil engines. Atlas-Imperial of Oakland, Union, and Lister diesels appear.
- 1924 - First diesel trucks appear.
- 1928 - Canadian National Railways employ a diesel shunter in their yards.
- 1930s - Clessie Cummins starts with Dutch diesel engines and then builds his own into trucks, and a Duesenberg luxury car at the Daytona speedway.
- 1930s - Caterpillar tractor start building diesels for their tractors.
- 1934 - General Motors starts a GM diesel research faciility. It builds diesel railroad engines--The Pioneer Zephyr, and goes on to found the General Motors Electro-Motive Division, which becomes important building engines for landing craft and tanks in the Second World War. GM then applies this knowledge to market control with its famous ‘Green Leakers” for buses, and railroad engines.

- 1936 - Mercedes-Benz builds the 260D diesel car. A.T.S.F inaugerates the diesel train Super Chief
- 1936 - Airship Hindenburg powered by diesel engines.

How diesel engines work

When a gas is compressed, its temperature rises (see the combined gas law); a diesel engine uses this property to ignite the fuel. Air is drawn into the cylinder of a diesel engine and compressed by the rising piston at a much higher compression ratio than for a spark-ignition engine, up to 25:1. The air temperature reaches 700–900 °C, or 1300–1650 °F. At the top of the piston stroke, diesel fuel is injected into the combustion chamber at high pressure, through an atomising nozzle, mixing with the hot, high-pressure air. The resulting mixture ignites and burns very rapidly. This contained combustion causes the gas in the chamber to heat up rapidly, which increases its pressure, which in turn forces the piston downwards. The connecting rod transmits this motion to the crankshaft, which is forced to turn, delivering rotary power at the output end of the crankshaft. Scavenging (pushing the exhausted gas-charge out of the cylinder, and drawing in a fresh draught of air) of the engine is done either by ports or valves. To fully realize the capabilities of a diesel engine, use of a turbocharger to compress the intake air is necessary; use of an aftercooler/intercooler to cool the intake air after compression by the turbocharger further increases efficiency.

In very cold weather, diesel fuel thickens and increases in viscosity and forms wax crystals or a gel. This can make it difficult for the fuel injector to get fuel into the cylinder in an effective manner, making cold weather starts difficult at times, though recent advances in diesel fuel technology have made these difficulties rare. A commonly applied advance is to electrically heat the fuel filter and fuel lines. Other engines utilize small electric heaters called glow plugs inside the cylinder to warm the cylinders prior to starting. A small number use resistive grid heaters in the intake manifold to warm the inlet air until the engine reaches operating temperature. Engine block heaters (electric resistive heaters in the engine block) plugged into the utility grid are often used when an engine is shut down for extended periods (more than an hour) in cold weather to reduce startup time and engine wear.

A vital component of older diesel engine systems was the governor, which limited the speed of the engine by controlling the rate of fuel delivery. Unlike a petrol (gasoline) engine, the incoming air is not throttled, so the engine would overspeed if this was not done. Older injection systems were driven by a gear system from the engine (and thus supplied fuel only linearly with engine speed). Modern electronically-controlled engines apply similar control to petrol engines and limit the maximum RPM through the electronic control module (ECM) or electronic control unit (ECU) - the engine-mounted "computer". The ECM/ECU receives an engine speed signal from a sensor and then using its algorithms and look-up calibration tables stored in the ECM/ECU, it controls the amount of fuel and its timing (the "start of injection") through electric or hydraulic actuators to maintain engine speed.

Controlling the timing of the **start of injection** of fuel into the cylinder is key to minimising the emissions, and maximising the fuel economy (efficiency), of the engine. The exact timing of starting this fuel injection into the cylinder is controlled electronically in most of today's modern engines. The timing is usually measured in units of crank angle of the piston before Top Dead Center (TDC). For example, if the ECM/ECU initiates fuel injection when the piston is 10 degrees before TDC, the start of injection or "timing" is said to be 10 deg BTDC. The optimal timing will depend on both the engine design as well as its speed and load.

Advancing (injecting when the piston is further away from TDC) the start of injection results in higher in-cylinder pressure, temperature, and higher efficiency but also results in higher emissions of Oxides of Nitrogen (NOx) due to the higher temperatures. At the other extreme, very retarded start of injection or timing causes incomplete combustion. This results in higher Particulate Matter (PM) and unburned hydrocarbon (HC) emissions and more smoke.

Fuel injection in diesel engines

Early Fuel Injection Systems

The modern diesel engine is a combination of two inventors' creations. In all major aspects, it holds true to Diesel's original design, of the fuel being ignited by compression at extremely high cylinder pressures. However, nearly all present-day diesel engines use the so-called 'solid' injection system invented by Herbert Akroyd Stuart, for his hot bulb engine (a compression-ignition engine that precedes the diesel engine and operates slightly differently). 'Solid' injection is where the fuel is raised to extreme pressures by mechanical pumps and delivered to the combustion chamber by pressure-activated injectors in an almost solid-state jet. Diesel's original engine injected fuel with the assistance of compressed air, which atomised the fuel and forced it into the engine through a nozzle. This was 'air-blast' injection. The size of the compressor needed to power such a system made early diesel engines very heavy and large for their power outputs, and the need to drive a compressor lowered this power output even more. Early marine diesels often had smaller auxiliary engines whose sole purpose was to drive the compressors to supply air to the main engine's injector system. Such a system was too bulky and inefficient to be used for road-going automotive vehicles.

Solid injection systems are lighter, simpler and allow much faster engine speeds, and so are universally used for automotive diesel engines. Air-blast systems provide very efficient combustion under low-speed, high-load conditions, especially when running on poor-quality fuels, so some large 'cathedral' marine engines use this injection method. Air-blast injection also raises the fuel temperature during the injection process, so is sometimes known as 'hot-fuel' injection. In contrast, solid injection is sometimes called 'cold-fuel' injection.

Given that the vast majority of diesel engines in service today use solid injection, the information below relates to that system.

Mechanical and electronic injection

Older engines make use of a mechanical fuel pump and valve assembly which is driven by the engine crankshaft, usually from the timing belt or chain. These engines use simple injectors which are basically very precise spring-loaded valves which will open and close at a specific fuel pressure. The pump assembly consists of a pump which pressurizes the fuel, and a disc-shaped valve which rotates at half crankshaft speed. The valve has a single aperture to the pressurized fuel on one side, and one aperture for each injector on the other. As the engine turns the valve discs will line up and deliver a burst of pressurized fuel to the injector at the cylinder about to enter its power stroke. The injector valve is forced open by the fuel pressure and the diesel is injected until the valve rotates out of alignment and the fuel pressure to that injector is cut off. Engine speed is controlled by a third disc, which rotates only a few degrees and is controlled by the throttle lever. This disc alters the width of the aperture through which the fuel passes, and therefore how long the injectors are held open before the fuel supply is cut, controlling the amount of fuel injected.

Older diesel engines with mechanical injection pumps could be inadvertently run in reverse, albeit very inefficiently as witnessed by massive amounts of soot being ejected from the air intake. This was often a consequence of bump starting a vehicle using the wrong gear.

This contrasts with the more modern method of having a separate fuel pump (or set of pumps) which supplies fuel constantly at high pressure to each injector. Each injector then has a solenoid which is operated by an electronic control unit, which enables more accurate control of injector opening times depending on other control conditions such as engine speed and loading, resulting in better engine performance and fuel economy. This design is also mechanically simpler than the combined pump and valve design, making it generally more reliable, and less noisy, than its mechanical counterpart.

Both mechanical and electronic injection systems can be used in either direct or indirect injection configurations.

Indirect injection

Indirect injection

An indirect injection diesel engine delivers fuel into a chamber off the combustion chamber, called a prechamber, where combustion begins and then spreads into the main combustion chamber, assisted by turbulence created in the chamber. This system allows smoother, quieter running, and because combustion is assisted by turbulence, injector pressures can be lower, which in the days of mechanical injection systems allowed high-speed running suitable for road vehicles (typically up to speed of around 4,000 rpm). The prechamber had the disadvantage of increasing heat loss to the engine's cooling system and restricting the combustion burn, which reduced the efficiency by between 5-10% in comparison to a direct injection engine, and nearly all require some form of cold-start device such as glow plugs. Indirect injection engines were used widely in small-capacity high-speed diesel engines in automotive, marine and construction uses from the 1950s, until direct-injection technology advanced in the 1980s. Indirect injection engines are cheaper to build and it is easier to produce smooth, quiet running vehicles with a simple mechanical system, so such engines are still often used in applications which carry less stringent emissions controls than road-going vehicles, such as small marine engines, generators, tractors, pumps. With electronic injection systems, indirect injection engines are still used in some road-going vehicles, but most prefer the greater efficiency of direct injection.

Direct injection

Modern diesel engines make use of one of the following direct injection methods:

Distributor pump direct injection

The first incarnations of direct injection diesels used a rotary pump much like indirect injection diesels, however the injectors were mounted in the top of the combustion chamber rather than in a separate pre-combustion chamber. Examples are vehicles such as the Ford Transit and the Austin Rover Maestro and Montego with their Perkins Prima engine. The problem with these vehicles was the harsh noise that they made and particulate (smoke) emissions. This is the reason that in the main this type of engine was limited to commercial vehicles— the notable exceptions being the Maestro, Montego and Fiat Croma passenger cars. Fuel consumption was about fifteen to twenty percent lower than indirect injection diesels, which for some buyers was enough to compensate for the extra noise.

One of the first small-capacity, mass-produced direct-injection engines that could be called refined was developed by the Rover Group.The '200Tdi' 2.5-litre 4-cylinder turbodiesel (of 111 horsepower) was used by Land Rover in their vehicles from 1989, and the engine used an aluminium cylinder head, Bosch two-stage injection and multi-phase glow plugs to produce a smooth-running and economical engine while still using mechanical fuel injection.

This type of engine was transformed by electronic control of the injection pump, pioneered by Volkswagen Audi group with the Audi 100 TDI introduced in 1989. The injection pressure was still only around 300 bar, but the injection timing, fuel quantity, exhaust gas recirculation and turbo boost were all electronically controlled. This gave much more precise control of these parameters which made refinement much more acceptable and emissions acceptably low. Fairly quickly the technology trickled down to more mass market vehicles such as the Mark 3 Golf TDI where it proved to be very popular. These cars were both more economical and more powerful than indirect injection competitors of their day.

Common rail direct injection

Common rail

In older diesel engines, a distributor-type injection pump, regulated by the engine, supplies bursts of fuel to injectors which are simply nozzles through which the diesel is sprayed into the engine's combustion chamber.

In common rail systems, the distributor injection pump is eliminated. Instead an extremely high pressure pump stores a reservoir of fuel at high pressure - up to 1,800 bar (180 MPa, 26,000 psi) - in a "common rail", basically a tube which in turn branches off to computer-controlled injector valves, each of which contains a precision-machined nozzle and a plunger driven by a solenoid,or even by piezo-electric actuators, which are found on experimental diesel race car engines.

Most European automakers have common rail diesels in their model lineups, even for commercial vehicles. Some Japanese manufacturers, such as Toyota, Nissan and recently Honda, have also developed common rail diesel engines.

Different car makers refer to their common rail engines by different names, e.g. DaimlerChrysler's CDI, Ford Motor Company's TDCi (most of these engines are manufactured by PSA), Fiat Group's (Fiat, Alfa Romeo and Lancia) JTD, Renault's DCi, GM/Opel's CDTi (most of these engines are manufactured by Fiat, other by Isuzu), Hyundai's CRDi, Mitsubishi's DI-D, PSA Peugeot Citroën's HDi (Engines for commercial diesel vehicles are made by Ford Motor Company), Toyota's D-4D, and so on.

Unit direct injection

This also injects fuel directly into the cylinder of the engine. However, in this system the injector and the pump are combined into one unit positioned over each cylinder. Each cylinder thus has its own pump, feeding its own injector, which prevents pressure fluctuations and allows more consistent injection to be achieved. This type of injection system, also developed by Bosch, is used by Volkswagen AG in cars (where it is called

Pumpe Düse - literally "pump nozzle"), Mercedes Benz (PLD) and most major diesel engine manufacturers, in large commercial engines (Cat, Cummins, Detroit Diesel). With recent advancements, the pump pressure has been raised to 2,050 bar (205 MPa), allowing injection parameters similar to common rail systems.

Hypodermic injection injury hazard

Because many diesel engine fuel injection systems operate at extremely high pressure, there is a risk of injury by hypodermic injection of fuel, if the fuel injector is removed from its seat and operated in open air.

Types of diesel engines

There are two classes of diesel (and gasoline) engines: two-stroke and four-stroke. Most diesels generally use the four-stroke cycle, with some larger diesels operating on the two-stroke cycle, mainly the huge engines in ships. Most modern locomotives use a two-stroke diesel mated to a generator, which produces current to drive electric motors, eliminating the need for a transmission. To achieve operational pressure in the cylinders, two-stroke diesels must utilize forced aspiration from either a turbocharger or supercharger. Diesel two-strokes are ideal for such applications because of their high power density--with twice as many power strokes per crankshaft revolution compared to a four-stroke, they are capable of producing much more power per displacement.

Normally, banks of cylinders are used in multiples of two, although any number of cylinders can be used as long as the load on the crankshaft is counterbalanced to prevent excessive vibration. The inline-6 is the most prolific in medium- to heavy-duty engines, though the V8 and straight-4 are also common.

As a footnote, prior to 1949, Sulzer started experimenting with two-stroke engines with boost pressures as high as 6 atmospheres, in which all of the output power was taken from an exhaust turbine. The two-stroke pistons directly drove air compressor pistons to make a positive displacement gas generator. Opposed pistons were connected by linkages instead of crankshafts. Several of these units could be connected together to provide power gas to one large output turbine. The overall thermal efficiency was roughly twice that of a simple gas turbine. (Source *Modern High-Speed Oil Engines Volume II* by C. W. Chapman published by The Caxton Publishing Co. Ltd. reprinted in July 1949)

Carbureted compression ignition model engines

Simple compression ignition engines are made for model propulsion. This is quite similar to the typical glow-plug engine that runs on a mixture of methanol (methyl alcohol) and lubricant (typically castor oil) (and occasionally nitro-methane to improve performance) with a hot wire filament to provide ignition. Rather than containing a glow plug the head has an adjustable *contra piston* above the piston, forming the upper surface of the combustion chamber. This contra piston is restrained by an adjusting screw controlled by an external lever (or sometimes by a removable hex key). The fuel used contains ether, which is highly volatile and has an extremely low flash point, combined with kerosene and a lubricant plus a very small proportion (typically 2%) of ignition improver such as Amyl nitrate or preferably Isopropyl nitrate nowadays. The engine is started by reducing the compression and setting the spray bar mixture rich with the adjustable needle valve, gradually increasing the compression while cranking the engine. The compression is increased until the engine starts running. The mixture can then be leaned out and the compression increased. Compared to glow plug engines, model diesel engines exhibit much higher fuel economy, thus increasing endurance for the amount of fuel carried. They also exhibit higher torque, enabling the turning of a larger or higher pitched propellor at slower speed. Since the combustion occurs well before the exhaust port is uncovered, these engines are also considerably quieter (when unmuffled) than glow-plug engines of similar displacement. Compared to glow plug engines, model diesels are more difficult to throttle over a wide range of powers, making them less suitable for radio control models than either two or four stroke glow-plug engines although this difference is claimed to be less noticeable with the use of modern schneurle-ported engines.

Advantages and disadvantages versus spark-ignition engines

Power and fuel economy

Diesel engines are more efficient than gasoline (petrol) engines of the same power, resulting in lower fuel consumption. A common margin is 40% more miles per gallon for an efficient turbodiesel. For example, the current model Skoda Octavia, using Volkswagen engines, has a combined Euro mpg of 38 mpg for the 102 bhp petrol engine and 53 mpg for the 105 bhp diesel engine. However, such a comparison doesn't take into account that diesel fuel is denser and contains more energy, about 15% more. Adjusting the numbers for the Octavia, one finds the overall energy efficiency is still about 20% greater for the diesel version, despite the weight penalty of its engine. When comparing engines of relatively low power for the vehicle's weight (such as the 75 hp engines for the VW Golf), the diesel's overall energy efficiency advantage is reduced further still, to between 10 and 15 percent.

While higher compression ratio is helpful in raising efficiency, diesel engines are much more economical than gasoline (petrol) engines when at low power and at engine idle. Unlike the petrol engine, diesels lack a butterfly valve (choke) in the inlet system, which closes at idle. This creates parasitic drag on the incoming air, reducing the efficiency of petrol/gasoline engines at idle. Due to their lower heat losses, diesel engines rarely run the risk of gradually overheating if left idling for a long period of time providing the cooling system is in good order. In many applications, such as marine, agriculture and railways, diesel-engined vehicles are left idling unattended for many hours or sometimes days. These advantages are especially attractive in locomotives (see dieselization for more information).

Naturally aspirated diesel engines are heavier than gasoline engines of the same power for two reasons. The first is that it takes a larger displacement diesel engine to produce the same power as a gasoline engine. This is essentially because the diesel must operate at lower engine speeds. Diesel fuel is injected just before ignition, leaving the fuel little time to "find" all the oxygen in the cylinder. In the gasoline engine, air and fuel are mixed for the entire compression stroke, ensuring complete mixing even at higher engine speeds. The second reason for the greater weight of a diesel engine is it must be stronger to withstand the higher combustion pressures needed for ignition, and the shock loading from the detonation of the ignition mixture. As a result, the reciprocating mass (the piston and connecting rod), and the resultant forces to accelerate and to decelerate these masses, are substantially higher the heavier, the bigger and the stronger the part, and the laws of diminishing returns of component strength, mass of component and inertia - all come into play to create a balance of offsets, of optimal mean power output, weight and durability.

Yet it is this same build quality that has allowed some enthusiasts to acquire significant power increases with turbocharged engines through fairly simple and inexpensive modifications. A gasoline engine of similar size cannot put out a comparable power increase without extensive alterations because the stock components would not be able to withstand the higher stresses placed upon them. Since a diesel engine is already built to withstand higher levels of stress, it makes an ideal candidate for performance tuning with little expense. However it should be said that any modification that raises the amount of fuel and air put through a diesel engine will increase its operating temperature which will reduce its life and increase its service interval requirements. These are issues with newer, lighter, "high performance" diesel engines which aren't "overbuilt" to the degree of older engines and are being pushed to provide greater power in smaller engines.

The addition of a turbocharger or supercharger to the engine (see turbodiesel) greatly assists in increasing fuel economy and power output, mitigating the fuel-air intake speed limit mentioned above for a given engine displacement. Boost pressures can be higher on diesels than gasoline engines, and the higher compression ratio allows a diesel engine to be more efficient than a comparable spark ignition engine. Although the calorific value of the fuel is slightly lower at 45.3 MJ/kg (megajoules per kilogram) to gasoline at 45.8 MJ/kg, diesel fuel is much denser and fuel is sold by volume, so diesel contains more energy per litre or gallon. The increased fuel economy of the diesel over the gasoline engine means that the diesel produces less carbon dioxide (CO_2) per unit distance. Recently, advances in production and changes in the political climate have increased the availability and awareness of biodiesel, an alternative to petroleum-derived diesel fuel with a much lower net-sum emission of CO_2, due to the absorption of CO_2 by plants used to produce the fuel.

The two main factors that held diesel engine back in private vehicles until quite recently were their low power outputs and high noise levels (characterised by knock or clatter, especially at low speeds and when cold). This noise was caused by the sudden ignition of the diesel fuel when injected into the combustion chamber. This noise was a product of the sudden temperature change, hence why it was more pronounced at low engine temperatures. A combination of improved mechanical technology (such as two-stage injectors which fire a short 'pilot charge' of fuel into the cylinder to warm the combustion chamber before delivering the main fuel charge) and electronic control (which can adjust the timing and length of the injection process to optimise it for all speeds and temperatures) have almost totally solved these problems in the latest generation of common-rail designs. Poor power and narrow torque bands have been solved by the use of turbochargers and intercoolers.

Emissions

Diesel engines produce very little carbon monoxide as they burn the fuel in excess air even at full load, at which point the quantity of fuel injected per cycle is still about 50% lean of stoichiometric. However, they can produce black soot (or more specifically Diesel particulate matter) from their exhaust, which consists of unburned carbon compounds. This is often caused by worn injectors, which do not atomize the fuel sufficiently, or a faulty engine management system which allows more fuel to be injected than can be burned completely in the available time.

The full load limit of a diesel engine in normal service is defined by the "black smoke limit", beyond which point the fuel cannot be completely combusted; as the "black smoke limit" is still considerably lean of stoichiometric it is possible to obtain more power by exceeding it, but the resultant inefficient combustion means that the extra power comes at the price of reduced combustion efficiency, high fuel consumption and dense clouds of smoke, so this is only done in specialised applications (such as tractor pulling) where these disadvantages are of little concern.

Particles of the size normally called PM10 (particles of 10 micrometres or smaller) have been implicated in health problems, especially in cities. Some modern diesel engines feature diesel particulate filters, which catch the black soot and when saturated are automatically regenerated by burning the particles. Other problems associated with the exhaust gases (nitrogen oxides, sulfur oxides) can be mitigated with further investment and equipment; some diesel cars now have catalytic converters in the exhaust.

Power and Torque

For commercial uses requiring towing, load carrying and other tractive tasks, diesel engines tend to have more desirable torque characterstics. Diesel engines tend to have their torque peak quite low in their speed range (usually between 1600-2000 rpm for a small-capacity unit, lower for a larger engine used in a lorry or truck). This provides smoother control over heavy loads when starting from rest, and crucially allows the diesel engine to be given higher loads at low speeds than a petrol/gasoline engine, which makes them much more economical for these applications. This characteristic is not so desirable in private cars, so most modern diesels used in such vehicles use electronic control, variable geometery turbochargers and shorter piston strokes to achieve a wider spread of torque over the engine's speed range, typically peaking at around 2500-3000 rpm.

Reliability

The lack of an electrical ignition system greatly improves the reliability. The high durability of a diesel engine is also due to its overbuilt nature (see above) as well as the diesel's combustion cycle, which creates less-violent changes in pressure when compared to a spark-ignition engine, a benefit that is magnified by the lower rotating speeds in diesels. Diesel fuel is a better lubricant than gasoline so is less harmful to the oil film on piston rings and cylinder bores; it is routine for diesel engines to cover 250,000 miles or more without a rebuild.

Unfortunately, due to the greater compression force required and the increased weight of the stronger components, starting a diesel engine is a harder task. More torque is required to push the engine through compression.

Either an electrical starter or an air start system is used to start the engine turning. On large engines, pre-lubrication and slow turning of an engine, as well as heating, are required to minimize the amount of engine damage during initial start-up and running. Some smaller military diesels can be started with an explosive cartridge, called a kaufman starter, that provides the extra power required to get the machine turning. In the past, Caterpillar and John Deere used a small gasoline "pony" motor in their tractors to start the primary diesel motor. The pony motor heated the diesel to aid in ignition and utilized a small clutch and transmission to actually spin up the diesel engine. Even more unusual was an International Harvester design in which the diesel motor had its own carburetor and ignition system, and started on gasoline. Once warmed up, the operator moved two levers to switch the motor to diesel operation, and work could begin. These engines had very complex cylinder heads (with their own gasoline combustion chambers) and in general were vulnerable to expensive damage if special care was not taken (especially in letting the engine cool before turning it off).

As mentioned above, diesel engines tend to have more torque at lower engine speeds than gasoline engines. However, diesel engines tend to have a narrower power band than gasoline engines. Naturally-aspirated diesels tend to lack power and torque at the top of their speed range. This narrow band is a reason why a vehicle such as a truck may have a gearbox with as many as 16 or more gears, to allow the engine's power to be used effectively at all speeds. Turbochargers tend to improve power at high engine speeds, intercoolers do the same at lower speeds, and variable geometry turbochargers improve the engine's performance equally (or make the torque curve flatter).

Quality and variety of fuels

Petrol/gasoline engines are limited in the variety and quality of the fuels they can burn. Older petrol engines fitted with a carburetor required a volatile fuel that would vaporise easily to create the necessary fuel/air mix for combustion. Because both air and fuel is admitted to the cylinder, if the compression ratio of the engine is too high or the fuel too volatile (with too low an octane rating, the fuel will ignite under compression, in a similar fashion to in a diesel engine, before the piston reaches the top of its stroke. This pre-ignition causes power loss and over time major damage to the piston and cylinder. The need for a fuel that is volatile enough to vaporise but not too volatile (too avoid pre-ignition) means that petrol engines will only run on a narrow range of petroleum-based fuels.

In diesel engines, a mechanical injector system vaporises the fuel (instead of a venturi jet in a carburetor as in a petrol engine). This 'forced vaporisation' means that less volatile fuels can be used. More crucially, because only air is inducted into the cylinder in a diesel engine, the compression ratio can be much higher as there is no risk of pre-ignition providing the injection process is accuratly timed. This means that cylinder temperatures are much higher in a diesel engine than a petrol engine allowing less combustible fuels to be used.

Diesel fuel is a form of light fuel oil, very similar to kerosene but diesel engines, especially older or simple designs that lack precision electronic injection systems, can run on a wide variety of other fuels. One of the most common alternatives is vegetable oil, which some engines can be run on without modification, and most others require fairly basic alterations. Bio-diesel is a pure diesel fuel refined from vegetable oil and can be used in nearly all diesel engines. The only limits on the fuels used in diesel engines are the ability of the fuel to flow along the fuel lines and the ability of the fuel to lubricate the injector pump and injectors adequately.

Most large marine diesels (often called 'cathedral engines' due to their size) run on heavy fuel oil, which is a thick, viscous and almost un-flammable fuel which is cheap to buy in bulk and safe to store. The fuel must be heated to thin it out and is often passed through multiple injection stages to vaporise it.

Dieseling in spark-ignition engines

A gasoline (spark ignition) engine can sometimes act as a compression ignition engine under abnormal circumstances, a phenomenon typically described as "pinging" or "pinking" (during normal running) or "dieseling" (when the engine continues to run after the electrical ignition system is shut off). This is usually caused by hot carbon deposits within the combustion chamber that act as would a "glow plug" within a diesel or model aircraft engine. Excessive heat can also be caused by improper ignition timing and/or fuel/air ratio which in turn overheats the exposed portions of the spark plug within the combustion chamber. Finally, high-compression engines that require high octane fuel may knock when a lower-octane fuel is used.

Fuel and fluid characteristics

Diesel

Diesel engines can operate on a variety of different fuels, depending on configuration, though the eponymous diesel fuel derived from crude oil is most common. Good-quality diesel fuel can be synthesised from vegetable oil and alcohol. Biodiesel is growing in popularity since it can frequently be used in unmodified engines, though production remains limited. Petroleum-derived diesel is often called "petrodiesel" if there is need to distinguish the source of the fuel.

The engines can work with the full spectrum of crude oil distilates, from compressed natural gas, alcohols, gasolene, to the "fuel oils" from diesel oil to residual fuels. The type of fuel used is a combination of service requirements, and fuel costs.

"Residual fuels" are the "dregs" of the distilation process and are a thicker, heavier oil, or oil with higher viscosity, which are so thick that they are not readily pumpable unless heated. Residual fuel oils are cheaper than clean, refined diesel oil, although they are dirtier. Their main considerations are for use in ships and very large generation sets, due to the cost of the large volume of fuel consumed, frequently amounting to many tonnes per hour. The poorly refined biofuels straight vegetable oil (SVO) and waste vegetable oil (WVO) can fall into this category. Moving beyond that, use of low-grade fuels can lead to serious maintenance problems. Most diesel engines that power ships like supertankers are built so that the engine can safely use low grade fuels.

Normal diesel fuel is more difficult to ignite than gasoline because of its higher flash point, but once burning, a diesel fire can be fierce.

Diesel applications

The vast majority of modern heavy road vehicles (trucks), ships, large-scale portable power generators, most farm and mining vehicles, and many long-distance locomotives have diesel engines. See dieselisation

Besides their use in merchant ships and boats, there is also a naval advantage in the relative safety of diesel fuel, additional to improved range over a gasoline engine. The German "pocket battleships" were the largest diesel warships, but the German torpedo-boat called "Schnellboot" of the Second World War was also a diesel craft. Conventional submarines have used them since before the First World War. It was an advantage of American diesel-electric submarines that they operated a two-stroke cycle as opposed to the four-stroke cycle that other navies used.

Mercedes-Benz, cooperating with Robert Bosch GmbH, has a successful run of diesel-powered passenger cars since 1936, sold in many parts of the World, with other manufacturers joining in the 1970s and 1980s. The second car manufacturer was Peugeot, prior to 1960.

In the United States, probably due to some hastily offered cars in the 1980s, diesel is not as popular in passenger vehicles as in Europe. Such cars have been traditionally perceived as heavier, noisier, having performance characteristics which make them slower to accelerate, and of being more expensive than equivalent gasoline vehicles. General Motors Oldsmobile division produced a variation of its gasoline-powered V8 engine which is the main reason for this reputation. This image certainly does not reflect recent designs, especially where the very high low-rev torque of modern diesels is concerned — which have characteristics similar to the big V8 gasoline engines popular in the US. Light and heavy trucks, in the U.S., have been diesel-optioned for years.

European governments tend to favor diesel engines in taxation policy because of diesel's superior fuel efficiency. In addition, diesel fuel used in North America still has higher sulphur content than the fuel used in Europe, effectively limiting diesel use to industrial vehicles, before the introduction of 15 parts per million ultra-low sulfur diesel, which will start at 15 October 2006 in the U.S. (1 June 2006 in Canada). Ultra-low sulfur diesel is not mandatory until 2010 in the US.

In Europe, where tax rates in many countries make diesel fuel much cheaper than gasoline, diesel vehicles are very popular and newer designs have significantly narrowed differences between petrol and diesel vehicles in the areas mentioned. Often, among comparably designated models, the turbodiesels outperform their naturally aspirated petrol-powered sister cars. One anecdote tells of Formula One driver Jenson Button, who was arrested while driving a diesel-powered BMW 330cd Coupé at 230 km/h (about 140 mph) in France, where he was too young to have a gasoline-engined car hired to him. Button dryly observed in subsequent interviews that he had actually done BMW a public relations service, as nobody had believed a diesel could be driven that fast. Yet, BMW had already won the 24 Hours Nürburgring overall in 1998 with a 3-series diesel. The BMW diesel lab in Steyr, Austria is led by Ferenc Anisits and develops innovative diesel engines.

Mercedes-Benz, offering diesel-powered passenger cars since 1936, has put the emphasis on high performance diesel cars in its newer ranges, as does Volkswagen with its brands. Citroën sells more cars with diesel engines than gasoline engines, as the French brands (also Peugeot) pioneered smoke-less *HDI* designs with filters. Even the Italian marque Alfa Romeo, known for design and successful history in racing, focuses on Diesels that are also raced.

A few motorcycles have been built using diesel engines, but the weight and cost disadvantages generally outweigh the efficiency gains in this application.

High-speed

High-speed (approximately 1200 rpm and greater) engines are used to power trucks (lorries), buses, tractors, cars, yachts, compressors, pumps and small generators.

Medium-speed

Large electrical generators are driven by medium speed engines, (approximately 300 to 1200 rpm) optimised to run at a set speed and provide a rapid response to load changes.

Low-speed

The largest diesel engines are used to power ships. These monstrous engines have power outputs over 80MW, turn at about 60 to 100 rpm, and are up to 15 m tall. They often run on cheap low-grade fuel, which require extra heat treatment in the ship for tanking and before injection due to their low volatility. Companies such as Burmeister & Wain and Wärtsilä (e.g., Sulzer Diesels) design such large low speed engines. They are unusually narrow and tall due to the addition of a crosshead bearing. Today (2006), the 12 cylinder MAN B&W Diesel K98MC turbocharged two-stroke diesel engine build by MAN B&W Diesel licencee Hyundai Heavy Industries in Korea is the most powerful diesel engine put into service, with a cylinder bore of 980 mm delivering 74.8 MW (101,640 bhp). When put into service in 2007, the 14 cylinder Wärtsilä-Sulzer RTA96-C will become the most powerful diesel engine with 80 MW (110,000 hp).

Unusual applications

Aircraft

aircraft diesel engine

The zeppelins *Graf Zeppelin II* and *Hindenburg* were propelled by *reversible* diesel engines. The direction of operation was changed by shifting gears on the camshaft. From full power forward, the engines could be brought to a stop, changed over, and brought to full power in reverse in less than 60 seconds.

Diesel engines were first tried in aircraft in the 1930s. A number of manufacturers built engines, the best known probably being the Junkers Jumo 205, which was moderately successful, but proved unsuitable for combat use in WWII. Postwar, another interesting proposal was the complex Napier Nomad. In general, though, the lower power-to-weight ratio of diesels, particularly compared to kerosene-powered turboprop engines, has precluded their use in this application.

The very high cost of avgas in Europe, and the advances in automotive diesel technology, have seen renewed interest in the concept. New, certified diesel-powered light planes are already available, and a number of other companies are also developing new engine and aircraft designs for the purpose. Many of these run on the readily-available jet fuel, or can run on both jet fuel or conventional automotive diesel.

Automobile racing

Although the weight and lower output of a diesel engine tend to keep them away from automotive racing applications, there are many diesels being raced in classes that call for them, mainly in truck racing and tractor pulling, as well in types of racing where these drawbacks are less severe, such as land speed record racing or endurance racing. Even Diesel engined dragsters exist, despite the diesel's drawbacks being central to performance in this sport.

1931 - Clessie Cummins installs his Diesel in a race car. It runs at 162 km/h in Daytona, and 138 km/h in Indianapolis where it places 12th.

In 1933, A 1925 Bentley with a Gardner 4LW engine was the first diesel-engined car to take part in the Monte Carlo Rally when it was driven by Lord Howard de Clifford. It was the leading British car and finished fifth overall.

In 1952, Cummins Diesel won the pole at the Indianapolis 500 race with a supercharged 3 liter diesel car, relying on torque and fuel efficiency to overcome weight and low peak power, and led most of the race until the badly situated air intake of the car swallowed enough debris from the track to disable the car.

With turbocharged Diesel-cars getting stronger in the 1990s, they were also entered in touring car racing, and BMW even won the 24 Hours Nürburgring in 1998 with a 320d, against other factory-entered Diesel-competition of Volkswagen and about 200 normally powered cars. Alfa Romeo even organized a racing series with their Alfa Romeo 147 1.9 JTD models.

The VW Dakar Rally entrants for 2005 and 2006 are powered by their own line of TDI engines in order to challenge for the first overall diesel win there. Meanwhile, the five time 24 Hours of Le Mans winner Audi R8 race car was replaced by the Audi R10 in 2006, which is powered by a 650 hp (485 kW) and 1100 N·m (810 lbf·ft) V12 TDI common rail diesel engine, mated to a 5-speed gearbox, instead of the 6 used in the R8, to handle the extra torque produced. The gearbox is considered the main problem, as earlier attempts by others failed due to the lack of suitable transmissons that could stand the torque long enough.

After winning the 12 Hours of Sebring in 2006 with their Diesel-powered R10, Audi obtained the overall win at the 2006 24 Hours of Le Mans, too. This is the first time a sports car can compete for overall victories with Diesel-fuel against cars powered with regular fuel or methanol and bio-ethanol. However, the significance of this is slightly lessened by the fact that the ACO/ALMS race rules encourage the use of alternate fuels such as diesel.

Motorcycles

With a traditionally poor power-to-weight ratio, diesel engines are generally unsuited to use in a motorcycle, which requires high power, light weight and a fast-revving engine. However, in the 1980s NATO forces in Europe standardised all their vehicles to diesel power. Some had fleets of motorcycles, and so trials were conducted with diesel engines for these. Air-cooled single-cylinder engines built by Lombardini of Italy were used and had some success, achieving similar performance to petrol bikes and fuel usage of nearly 200 miles per gallon. This led to some countries re-fitting their bikes with diesel power.

Development by Cranfield University and California-based Hayes Diversified Technologies led to the production of a diesel powered off road motorbike based on the running gear of a Kawasaki KLR650 petrol-engine trail bike for military use. The engine of the diesel motorcycle is a liquid cooled, single cylinder four- stroke which displaces 584 cm^3 and produces 21 kw (28 bhp) with a top speed of 85mph (136kph). Hayes Diversified Technologies mooted, but has subsequently delayed, the delivery of a civilian version for approx USD$19,000. Expensive compared to comparable models.

In 2005 the United States Marine Corps adopted the M1030M1, a dirtbike based on the Kawasaki KLR650 and modified with an engine designed to run on diesel or JP8 jet fuel. Since other U.S. tactical vehicles like the Humvee utility vehicle and M1 Abrams tank use JP8, adopting a scout motorcycle which runs on the same fuels made sense from a logistical standpoint.

In India, motorcycles built by Royal Enfield can be bought with 650cc single-cylinder diesel engines based on the similar petrol engines used, due to the fact that diesel is much cheaper than petrol and of more reliable quality. These engines are noisy and unrefined, but very popular due to their reliability and economy.

Current and future developments

Already, many common rail and unit injection systems employ new injectors using stacked piezoelectric crystals in lieu of a solenoid, which gives finer control of the injection event.

Variable geometry turbochargers have flexible vanes, which move and let more air into the engine depending on load. This technology increases both performance and fuel economy. Boost lag is reduced as turbo impeller inertia is compensated for.

Accelerometer pilot control (APC) uses an accelerometer to provide feedback on the engine's level of noise and vibration and thus instruct the ECU to inject the minimum amount of fuel that will produce quiet combustion and still provide the required power (especially while idling.)

The next generation of common rail diesels are expected to use variable injection geometry, which allows the amount of fuel injected to be varied over a wider range, and variable valve timing similar to that on gasoline engines.

Particularly in the United States, coming tougher emissions regulations present a considerable challenge to diesel engine manufacturers. Other methods to achieve even more efficient combustion, such as HCCI (homogeneous charge compression ignition), are being studied.

Modern diesel facts

Common rail

Fuel passes through the injector jets at speeds of nearly 1500 miles per hour (2400 km/h) – as fast as the top speed of a jet plane.

Fuel is injected into the combustion chamber in less than 1.5 ms – about as long as a camera flash.

The smallest quantity of fuel injected is one cubic millimetre – about the same volume as the head of a pin. The largest injection quantity at the moment for automobile diesel engines is around 70 cubic millimetres.

If the camshaft of a six-cylinder engine is turning at 4500 rpm, the injection system has to control and deliver 225 injection cycles per second.

On a demonstration drive, a Volkswagen 1-litre diesel-powered car used only 0.89 litres of fuel in covering 100 kilometres (264 mpg {US}, 317 mpg {Imperial/English}) – making it probably the most fuel-efficient car in the world. Bosch’s high-pressure fuel injection system was one of the main factors behind the prototype’s extremely low fuel consumption. Production record-breakers in fuel economy include the Volkswagen Lupo 3 L TDI and the Audi A2 3 L 1.2 TDI with standard consumption figures of 3 litres of fuel per 100 kilometres (78 mpg {US}, 94 mpg {Imperial}). Their high-pressure diesel injection systems are also supplied by Bosch.

In 2001, nearly 36% of newly registered cars in Western Europe had diesel engines. By way of comparison: in 1996, diesel-powered cars made up only 15% of the new car registrations in Germany. Austria leads the league table of registrations of diesel-powered cars with 66%, followed by Belgium with 63% and Luxembourg with 58%. Germany, with 34.6% in 2001, was in the middle of the league table. Sweden is lagging behind, in 2004 only 8% of the new cars had diesel engine.

Diesel car history

The first production diesel cars were the Mercedes-Benz 260D and the Hanomag Rekord, both introduced in 1936. The Citroën Rosalie was also produced between 1935 and 1937 with an extremely rare diesel engine option (the 1766 cc 11UD engine) only in the Familiale (estate or station wagon) version.

Following the 1970s oil crisis, turbo diesels were tested, e. g. by the Mercedes-Benz C111 experimental and record-setting vehicles. The first production turbo diesel car was, in 1978, the 3.0 5-cyl 115 HP Mercedes 300 SD, available only in North America. In Europe, the Peugeot 604 with a 2.3 litre turbo diesel was introduced in 1979, and then the Mercedes 300 TD turbo.

Many Audi enthusiasts claim that the Audi 100 TDI was the first turbo charged direct injection diesel sold in 1989, but actually it isn't true, as the Fiat Croma TD-i.d. was sold with turbo direct injection in 1986 and 2 years later Austin Rover Montego.

What was pioneering about the Audi 100 however was the use of electronic control of the engine, as the Fiat and Austin had purely mechanically controlled injection. The electronic control of direct injection really made a difference in terms of emissions, refinement and power.

It's interesting to see that the big players in the diesel car market are the same ones who pioneered various developments (Mercedes, BMW, Peugeot/Citroën, Fiat, Alfa Romeo, VW/Audi/SEAT/Skoda), with the exception of Austin Rover.

In 1998, for the very first time in the history of racing, in the legendary 24 Hours Nürburgring race, a diesel-powered car was the overall winner: the BMW works team 320d, a BMW E36 fitted with modern high-pressure diesel injection technology from Robert Bosch GmbH. The low fuel consumption and long range, allowing 4 hours of racing at once, made it a winner, as comparable petrol-powered cars spent more time refuelling.

In 2006, the new Audi R10 TDI LMP1 entered by Joest Racing became the first Diesel-engined car to win the 24 Hours of Le Mans. The winning car also bettered the post-1990 course configuration lap record by 1, at 380. However, this fell short of the all-time distance record set in 1971 by over 200 km.ss

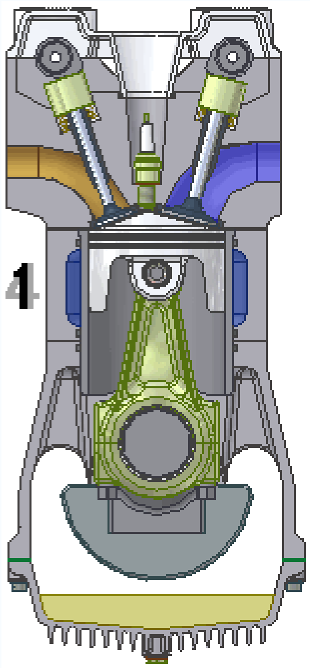
Internal combustion engine

A colorized automobile engine

The **internal combustion engine** is a heat engine in which the burning of a fuel occurs in a confined space called a combustion chamber. This exothermic reaction of a fuel with an oxidizer creates gases of high temperature and pressure, which are permitted to expand. The defining feature of an internal combustion engine is that useful work is performed by the expanding hot gases acting directly to cause movement, for example by acting on pistons, rotors, or even by pressing on and moving the entire engine itself.

This contrasts with external combustion engines such as steam engines which use the combustion process to heat a separate working fluid, typically water or steam, which then in turn does work, for example by pressing on a steam actuated piston.

The term *Internal Combustion Engine* (ICE) is almost always used to refer specifically to reciprocating engines, Wankel engines and similar designs in which combustion is intermittent. However, continuous combustion engines, such as Jet engines, most rockets and many gas turbines are also internal combustion engines.



Four-stroke cycle (or Otto cycle)
1. intake
2. compression
3. power
4. exhaust

History

The first internal combustion engines did not have compression, but ran on what air/fuel mixture could be sucked or blown in during the first part of the intake stroke. The most significant distinction between **modern internal combustion engines** and the early designs is the use of compression and in particular of in-cylinder compression.

- 1509: Leonardo da Vinci described a compression-less engine. (His description may not imply that the idea was original with him or that it was actually built.)
- 1673: Christiaan Huygens described a compression-less engine.

1780's: Alessandro Volta built a toy electric pistol () in which an electric spark exploded a mixture of air and hydrogen, firing a cork from the end of the gun.

Demonstration of the internal combustion indirect or suction principle. This may not meet the definition of an engine, because the process does not repeat.

Early internal-combustion engines were used to power farm equipment similar to these models.

- 17th century: English inventor Sir Samuel Morland used gunpowder to drive water pumps.
- 1794: Robert Street built a compression-less engine whose principle of operation would dominate for nearly a century.
- 1806: Swiss engineer François Isaac de Rivaz built an internal combustion engine powered by a mixture of hydrogen and oxygen.
- 1823: Samuel Brown patented the first internal combustion engine to be applied industrially. It was compression-less and based on what Hardenberg calls the "Leonardo cycle," which, as this name implies, was already out of date at that time. Just as today, early major funding, in an area where standards had not yet been established, went to the best showmen sooner than to the best workers.
- 1824: French physicist Sadi Carnot established the thermodynamic theory of idealized heat engines. This scientifically established the need for compression to increase the difference between the upper and lower working temperatures, but it is not clear that engine designers were aware of this before compression was already commonly used. It may have misled designers who tried to emulate the Carnot cycle in ways that were not useful.
- 1826 April 1: The American Samuel Morey received a patent for a compression-less "Gas Or Vapor Engine".
- 1838: a patent was granted to William Barnet (English). This was the first recorded suggestion of in-cylinder compression. He apparently did not realize its advantages, but his cycle would have been a great advance if developed enough.
- 1854: The Italians Eugenio Barsanti and Felice Matteucci patented the first working efficient internal combustion engine in London (pt. Num. 1072) but did not get into production with it. It was similar in concept to the successful Otto Langen indirect engine, but not so well worked out in detail.
- 1860: Jean Joseph Etienne Lenoir (1822 - 1900) produced a gas-fired internal combustion engine closely similar in appearance to a horizontal double-acting steam beam engine, with cylinders, pistons, connecting rods, and flywheel in which the gas essentially took the place of the steam. This was the first internal combustion engine to be produced in numbers. His first engine with compression shocked itself apart.
- 1862: Nikolaus Otto designed an indirect-acting free-piston compression-less engine whose greater efficiency won the support of Langen and then most of the market, which at that time, was mostly for small stationary engines fueled by lighting gas.

- 1870: In Vienna Siegfried Marcus put the first mobile gasoline engine on a handcart.
- 1876: Nikolaus Otto working with Gottlieb Daimler and Wilhelm Maybach developed a practical four-stroke cycle (Otto cycle) engine. The German courts, however, did not hold his patent to cover all in-cylinder compression engines or even the four stroke cycle, and after this decision in-cylinder compression became universal.

Karl Benz

- 1879: Karl Benz, working independently, was granted a patent for his internal combustion engine, a reliable two-stroke gas engine, based on Nikolaus Otto's design of the four-stroke engine. Later Benz designed and built his own four-stroke engine that was used in his automobiles, which became the first automobiles in production.
- 1882: James Atkinson invented the Atkinson cycle engine. Atkinson’s engine had one power phase per revolution together with different intake and expansion volumes making it more efficient than the Otto cycle.
- 1891 - Herbert Akroyd-Stuart builds his oil engine leasing rights to Hornsby of England to build engines. They build the first cold start, compression ignition engines. In 1892 they install the first ones in a water pumping station.
- 1892: Rudolf Diesel develops his Carnot heat engine type motor burning powdered coal dust.
- 1893 February 23: Rudolf Diesel received a patent for the diesel engine.

- 1896: Karl Benz invented the boxer engine, also known as the horizontally opposed engine, in which the corresponding pistons reach top dead centre at the same time, thus balancing each other in momentum.
- 1900: Rudolf Diesel demonstrated the diesel engine in the 1900 *Exposition Universelle* (World's Fair) using peanut oil (see biodiesel).
- 1900: Wilhelm Maybach designed an engine built at Daimler Motoren Gesellschaft—following the specifications of Emil Jellinek—who required the engine to be named *Daimler-Mercedes* after his daughter. In 1902 automobiles with that engine were put into production by DMG.

Applications

Internal combustion engines are most commonly used for mobile propulsion systems. In mobile scenarios internal combustion is advantageous, since it can provide high power to weight ratios together with excellent fuel energy-density. These engines have appeared in almost all automobiles, motorbikes, many boats, and in a wide variety of aircraft and locomotives. Where very high power is required, such as jet aircraft, helicopters and large ships, they appear mostly in the form of gas turbines. They are also used for electric generators and by industry.

Internal combustion mechanics

The potato cannon uses basic principles behind any reciprocating internal combustion engine: If a tiny amount of high-energy fuel (like gasoline) is put into a small, enclosed space and ignited, an incredible amount of energy is released in the form of expanding gas. That energy can be used to propel a potato 500 feet. In this case, the energy is translated into potato motion. It can also be used for more interesting purposes. For example, a cycle can be created that allows one to set off explosions like this hundreds of times per minute, and if that energy can be harnessed in a useful way, it is the same as the core of a car engine!

Almost all cars currently use what is called a four-stroke combustion cycle to convert gasoline into motion. The four-stroke approach is also known as the Otto cycle, in honor of Nikolaus Otto, who patented it in 1876. The four strokes are:

1. Intake stroke
2. Compression stroke

3. Combustion stroke
4. Exhaust stroke

Operation

All **internal combustion engines** depend on the exothermic chemical process of combustion: the reaction of a fuel, typically with air, although other oxidisers such as nitrous oxide may be employed. Also see stoichiometry.

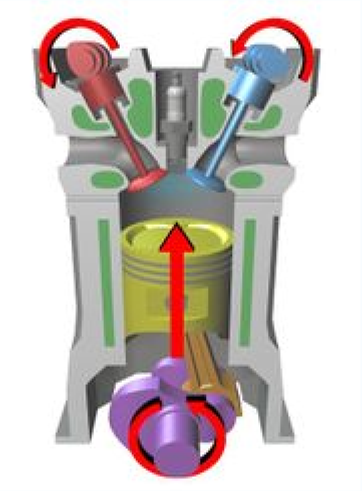
The most common fuels in use today are made up of hydrocarbons and are derived from petroleum. These include the fuels known as diesel, gasoline and liquified petroleum gas. Most internal combustion engines designed for gasoline can run on natural gas or liquified petroleum gases without modifications except for the fuel delivery components. Liquid and gaseous biofuels, such as Ethanol can also be used. Some can run on Hydrogen; however, this can be dangerous. Hydrogen burns with a colorless flame, and modifications to the cylinder block, cylinder head, and head gasket are required to seal in the flame front. Experimentation at Southwest Research Institute showed that without such modifications flame leaks from the exhaust manifolds were common. Since the flame was colorless, it was not visible to the naked eye. An invisible flame is more dangerous than a visible flame, since one cannot take into account what cannot be seen, and operator injury was regarded as a definite danger. However BMW has recently designed a 12-cylinder Hydrogen powered car, and the company has stated that it plans to market the vehicle.

All internal combustion engines must have a means of ignition to promote combustion. Most engines use either an electrical or a compression heating ignition system. Electrical ignition systems generally rely on a lead-acid battery and an induction coil to provide a high voltage electrical spark to ignite the air-fuel mix in the engine's cylinders. This battery can be recharged during operation using an alternator driven by the engine. Compression heating ignition systems, such as diesel engines and HCCI engines, rely on the heat created in the air by compression in the engine's cylinders to ignite the fuel.

Once successfully ignited and burnt, the combustion products, hot gases, have more available energy than the original compressed fuel/air mixture (which had higher chemical energy). The available energy is manifested as high temperature and pressure which can be translated into work by the engine. In a reciprocating engine, the high pressure product gases inside the cylinders drive the engine's pistons.

Once the available energy has been removed the remaining hot gases are vented (often by opening a valve or exposing the exhaust outlet) and this allows the piston to return to its previous position (Top Dead Center - TDC). The piston can then proceed to the next phase of its cycle, which varies between engines. Any heat not translated into work is a waste product and is removed from the engine either by an air or liquid cooling system.

Parts



An illustration of several key components in a typical four-stroke engine

The parts of an engine vary depending on the engine's type. For a four-stroke engine, key parts of the engine include the crankshaft (purple), one or more camshafts (red and blue) and valves. For a two-stroke engine, there may simply be an exhaust outlet and fuel inlet instead of a valve system. In both types of engines, there are one or more cylinders (grey and green) and for each cylinder there is a spark plug (darker-grey), a piston (yellow) and a crank (purple). A single sweep of the cylinder by the piston in an upward or downward motion is known as a stroke and the downward stroke that occurs directly after the air-fuel mix in the cylinder is ignited is known as a power stroke.

A Wankel engine has a triangular rotor that orbits in an epitrochoidal (figure 8 shape) chamber around an eccentric shaft. The four phases of operation (intake, compression, power, exhaust) take place in separate locations, instead of one single location as in a reciprocating engine.

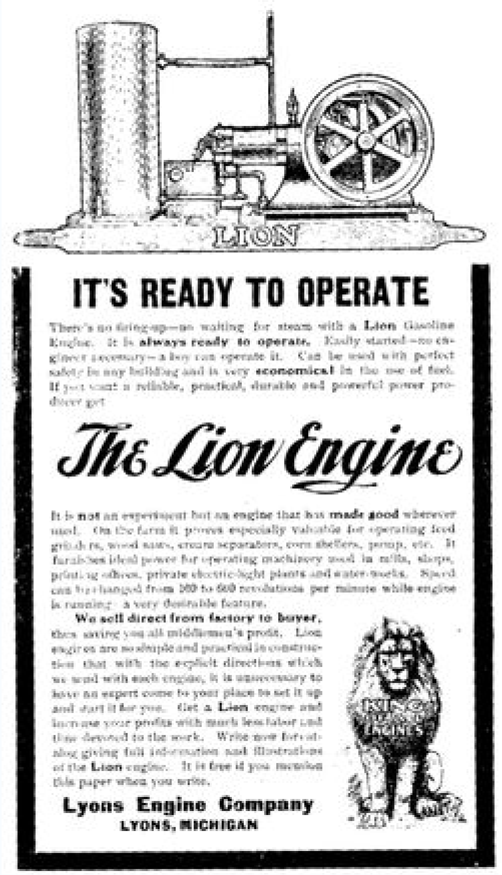
A Bourke Engine uses a pair of pistons integrated to a Scotch Yoke that transmits reciprocating force through a specially designed bearing assembly to turn a crank mechanism. Intake, compression, power, and exhaust all occur in each stroke of this yoke.

Classification

There is a wide range of internal combustion engines corresponding to their many varied applications. Likewise there is a wide range of ways to classify internal-combustion engines, some of which are listed below.

Although the terms sometimes cause confusion, there is no real difference between an "engine" and a "motor." At one time, the word "engine" (from Latin, via Old French, *ingenium*, "ability") meant any piece of machinery. A "motor" (from Latin *motor*, "mover") is any machine that produces mechanical power. Traditionally, electric motors are not referred to as "engines," but combustion engines are often referred to as "motors." (An *electric engine* refers to locomotive operated by electricity).

Principles of operation


LION
KING
ENGINES

IT'S READY TO OPERATE

There's no firing-up—no waiting for steam with a **Lion** Gasoline Engine. It is **always ready to operate.** Easily started—no engineer necessary—a boy can operate it. Can be used with perfect safety in any building and is very **economical** in the use of fuel. If you want a reliable, practical, durable and powerful power producer get

The Lion Engine

It is **not** an experiment but an **engine** that has **made good** wherever used. On the farm it proves especially valuable for operating feed grinders, wood saws, cream separators, corn shellers, pump, etc. It furnishes ideal power for operating machinery used in mills, shops, printing offices, private electric-light plants and water-works. Speed can be changed from [illegible] to [illegible] revolutions per minute while engine is running—a very desirable feature.

We sell direct from factory to buyer, thus saving you all middlemen's profit. Lion engines are so simple and practical in construction that with the explicit directions which we send with each engine, it is unnecessary to have an expert come to your place to set it up and start it for you. Get a **Lion** engine and increase your profits with much less labor and time devoted to the work. Write now for catalog giving full information and illustrations of the **Lion** engine. It is free if you mention this paper when you write.

Lyons Engine Company
LYONS, MICHIGAN

A 1906 gasoline engine

Reciprocating:

- Crude oil engine
- Two-stroke cycle
- Four-stroke cycle
- Hot bulb engine
- Poppet valves
- Sleeve valve
- Atkinson cycle

- Proposed
  - Bourke engine
- Improvements
- Controlled Combustion Engine

Rotary:

- Demonstrated:
    - Wankel engine
- Proposed:
    - Orbital engine
    - Quasiturbine
    - Rotary Atkinson cycle engine
    - Toroidal engine

Continuous combustion:

- Gas turbine
- Jet engine
- Rocket engine

Engine cycle

Two-stroke

Engines based on the two-stroke cycle use two strokes (one up, one down) for every power stroke. Since there are no dedicated intake or exhaust strokes, alternative methods must be used to scavenge the cylinders. The most common method in spark-ignition two-strokes is to use the downward motion of the piston to pressurize fresh charge in the crankcase, which is then blown through the cylinder through ports in the cylinder walls. Spark-ignition two-strokes are small and light (for their power output), and mechanically very simple. Common applications include snowmobiles, lawnmowers, weed-whackers, chain saws, jet skis, mopeds, outboard motors and some motorcycles. Unfortunately, they are also generally louder, less efficient, and far more polluting than their four-stroke counterparts, and they do not scale well to larger sizes. Interestingly, the largest compression-ignition engines are two-strokes, and are used in some locomotives and large ships. These engines use forced induction to scavenge the cylinders.

Four-stroke

Engines based on the four-stroke cycle or Otto cycle have one power stroke for every four strokes (up-down-up-down) and are used in cars, larger boats and many light aircraft. They are generally quieter, more efficient and larger than their two-stroke counterparts. There are a number of variations of these cycles, most notably the Atkinson and Miller cycles. Most truck and automotive Diesel engines use a four-stroke cycle, but with a compression heating ignition system. This variation is called the diesel cycle.

Bourke Engine

In this engine, two diametrically opposed cylinders are linked to the crank by the crank pin that goes through the common scottish yoke. The cylinders and pistons are so constructed that there are, as in the usual two stroke cycle, two power strokes per revolution. However, unlike the common two stroke engine, the burnt gases and the incoming fresh air do not mix in the cylinders, contributing to a cleaner, more efficient operation. The scotch yoke mechanism also has low side thrust and thus greatly reduces friction between pistons and cylinder walls. The Bourke cycle's combustion phase more closely approximates constant volume combustion than either four stroke or two stroke cycles do. It also uses less moving parts, hence needs to overcome less friction than the other two reciprocating types have to. In addition, its greater expansion ratio also means more of the heat from its combustion phase is utilized than is used by either four stroke or two stroke cycles.

Controlled Combustion Engine

These are also cylinder based engines may be either single or two stroke but use, instead of a crankshaft and piston rods, two gear connected, counter rotating concentric cams to convert reciprocating motion into rotary movement. These cams practically cancel out sideward forces that would otherwise be exerted on the cylinders by the pistons, greatly improving mechanical efficiency. The profiles of the cam lobes(which are always odd and at least three in number) determine the piston travel versus the torque delivered. In this engine, there are two cylinders that are 180 degrees apart for each pair of counter rotating cams. For single stroke versions, there are the same number of cycles per cylinder pair as there are lobes on each cam, twice as much for two stroke units.

Wankel

The Wankel engine operates with the same separation of phases as the four-stroke engine (but with no piston strokes, would more properly be called a four-phase engine), since the phases occur in separate locations in the engine; however like a two-stroke piston engine, it provides one power 'stroke' per revolution per rotor, giving it similar space and weight efficiency.

Gas turbine

With gas turbine cycles (notably Jet engines), rather than use the same piston to compress and then expand the gases, instead separate compressors and gas turbines are employed; giving continuous power. Essentially, the intake gas (air normally) is compressed, and then combusted with a fuel, which greatly raises the temperature and volume. The larger volume of hot gas from the combustion chamber is then fed through the gas turbine which is then easily able to power the compressor.

Disused methods

In some old non-compressing internal combustion engines: In the first part of the piston downstroke a fuel/air mixture was sucked or blown in. In the rest of the piston downstroke the inlet valve closed and the fuel/air mixture fired. In the piston upstroke the exhaust valve was open. This was an attempt at imitating the way a piston steam engine works.

Fuel and oxidizer types

Fuels used include petroleum spirit (North American term: gasoline, British term: petrol), liquified petroleum gas, vapourized petroleum gas, compressed natural gas, hydrogen, diesel fuel, jet fuel, landfill gas, biodiesel, biobutanol, peanut oil and other vegoils, bioethanol, biomethanol (methyl or wood alcohol) and other biofuels. Even fluidised metal powders and explosives have seen some use. Engines that use gases for fuel are called gas engines and those that use liquid hydrocarbons are called oil engines. However, gasoline engines are unfortunately also often colloquially referred to as 'gas engines'.

The main limitations on fuels are that the fuel must be easily transportable through the fuel system to the combustion chamber, and that the fuel release sufficient energy in the form of heat upon combustion to make use of the engine practical.

The oxidiser is typically air, and has the advantage of not being stored within the vehicle, increasing the power-to-weight ratio. Air can, however, be compressed and carried aboard a vehicle. Some submarines are designed to carry pure oxygen or hydrogen peroxide to make them air-independent. Some race cars carry nitrous oxide as oxidizer.

Other chemicals such as chlorine or fluorine have seen experimental use; but mostly are impractical.

Diesel engines are generally heavier, noisier and more powerful at lower speeds than gasoline engines. They are also more fuel-efficient in most circumstances and are used in heavy road vehicles, some automobiles (increasingly more so for their increased fuel efficiency over gasoline engines), ships, railway locomotives, and light aircraft. Gasoline engines are used in most other road vehicles including most cars, motorcycles and mopeds. Note that in Europe, sophisticated diesel-engined cars have become quite prevalent since the 1990s, representing around 40% of the market. Both gasoline and diesel engines produce significant emissions. There are also engines that run on hydrogen, methanol, ethanol, liquefied petroleum gas (LPG) and biodiesel. Paraffin and tractor vaporising oil (TVO) engines are no longer seen.

Some have theorized that in the future hydrogen might replace such fuels. Furthermore, with the introduction of hydrogen fuel cell technology, the use of internal combustion engines may be phased out. The advantage of hydrogen is that its combustion produces only water. This is unlike the combustion of fossil fuels, which produce carbon dioxide, a possible cause of global warming, as well as carbon monoxide, resulting from incomplete combustion. However, free hydrogen for fuel does not occur naturally, burning it liberates less energy than it takes to produce hydrogen in the first place by the simplest and most widespread method, electrolysis. Although there are multiple ways of producing free hydrogen, those require converting currently combustible molecules into hydrogen, so hydrogen does not solve any energy crisis, moreover, it only addresses the issue of portability and some pollution issues. The big disadvantage of hydrogen in many situations is its storage. Liquid hydrogen has extremely low density- 14 times lower than water and requires extensive insulation, whilst gaseous hydrogen requires very heavy tankage. Although hydrogen has a higher specific energy, the volumetric energetic storage is still roughly five times lower than petrol, even when liquified. (The 'Hydrogen on Demand' process, designed by Steven Amendola, creates hydrogen as it is needed, but this has other issues, such as the raw materials being relatively expensive.) Other fuels that are kinder on the environment include biofuels. These can give no net carbon dioxide gains.

One-cylinder gasoline engine (ca. 1910).

Cylinders

Internal combustion engines can contain any number of cylinders with numbers between one and twelve being common, though as many as 36 (Lycoming R-7755) have been used. Having more cylinders in an engine yields two potential benefits: First, the engine can have a larger displacement with smaller individual reciprocating masses (that is, the mass of each piston can be less) thus making a smoother running engine (since the engine tends to vibrate as a result of the pistons moving up and down). Second, with a greater displacement and more pistons, more fuel can be combusted and there can be more combustion events (that is, more power strokes) in a given period of time, meaning that such an engine can generate more torque than a similar engine with fewer cylinders. The down side to having more pistons is that, over all, the engine will tend to weigh more and tend to generate more internal friction as the greater number of pistons rub against the inside of their cylinders. This tends to decrease fuel efficiency and rob the engine of some of its power. For high performance gasoline engines using current materials and technology (such as the engines found in modern automobiles), there seems to be a break point around 10 or 12 cylinders, after which addition of cylinders becomes an overall detriment to performance and efficiency, although exceptions such as the W16 engine from Volkswagen exist.

- Most car engines have four to eight cylinders, with some high performance cars having ten, twelve, or even sixteen, and some very small cars and trucks having two or three. In previous years some quite large cars, such as the DKW and Saab 92, had two cylinder, two stroke engines.

- Radial aircraft engines, now obsolete, had from three to 28 cylinders, such as the Pratt & Whitney R-4360. A row contains an odd number of cylinders, so an even number indicates a two- or four-row engine. The largest of these was the Lycoming R-7755 with 36 cylinders (four rows of nine cylinders) but never entered production.
- Motor cycles commonly have from one to four cylinders, with a few high performance models having six (though some 'novelties' exist with 8, 10 and 12).
- Snowmobiles usually have two cylinders. Some larger (not necessarily high-performance, but also touring machines) have four.
- Small portable appliances such as chainsaws, generators and domestic lawn mowers most commonly have one cylinder, although two-cylinder chainsaws exist.

Ignition system

ignition system

Internal combustion engines can be classified by their ignition system. The point in the cycle at which the fuel/oxidiser mixture are ignited has a direct effect on the efficiency and output of the ICE. For a typical 4 stroke automobile engine, the burning mixture has to reach its maximum pressure when the crankshaft is 90 degrees after TDC. The speed of the flame front is directly affected by compression ratio, fuel mixture temperature and octane or cetane rating of the fuel. Modern ignition systems are designed to ignite the mixture at the right time to ensure the flame front doesn't contact the decending piston crown. If the flame front contacts the piston, pinking or knocking results. Leaner mixtures and lower mixture pressures burn more slowly requiring more advanced ignition timing. Today most engines use an electrical or compression heating system for ignition. However outside flame and hot-tube systems have been used historically. Nikola Tesla gained one of the first patents on the mechanical ignition system with U.S. Patent 609250, "*Electrical Igniter for Gas Engines*", on 16 August 1898.

Fuel systems

Fuel injection

Often for simpler reciprocating engines a carburetor is used to supply fuel into the cylinder. However, exact control of the correct amount of fuel supplied to the engine is impossible.

Larger gasoline engines such as used in cars have mostly moved to fuel injection systems (see Gasoline Direct Injection). Diesel engines always use fuel injection.

LPG engines use a mix of fuel injection systems and closed loop carburetors.

Other internal combustion engines like jet engines use burners, and rocket engines use various different ideas including impinging jets, gas/liquid shear, preburners and many other ideas.

Engine configuration

Internal combustion engines can be classified by their configuration which affects their physical size and smoothness (with smoother engines producing less vibration). Common configurations include the straight or inline configuration, the more compact V configuration and the wider but smoother flat or boxer configuration. Aircraft engines can also adopt a radial configuration which allows more effective cooling. More unusual configurations, such as "H", "U", "X", or "W" have also been used.

Multiple-crankshaft configurations do not necessarily need a cylinder head at all, but can instead have a piston at each end of the cylinder, called an opposed piston design. This design was used in the Junkers Jumo 205 diesel aircraft engine, using two crankshafts, one at either end of a single bank of cylinders, and most remarkably in the Napier Deltic diesel engines, which used three crankshafts to serve three banks of double-ended cylinders arranged in an equilateral triangle with the crankshafts at the corners. It was also used in single-bank locomotive engines, and continues to be used for marine engines, both for propulsion and for auxiliary generators. The Gnome Rotary engine, used in several early aircraft, had a stationary crankshaft and a bank of radially arranged cylinders rotating around it.

Engine capacity

An engine's capacity is the displacement or swept volume by the pistons of the engine. It is generally measured in litres or cubic inches for larger engines and cubic centimetres (abbreviated to cc) for smaller engines. Engines with greater capacities are usually more powerful and provide greater torque at lower rpm but also consume more fuel.

Apart from designing an engine with more cylinders, there are two ways to increase an engine's capacity. The first is to lengthen the stroke and the second is to increase the piston's diameter *(Stroke ratio)*. In either case, it may be necessary to make further adjustments to the fuel intake of the engine to ensure optimal performance.

An engine's quoted capacity can be more a matter of marketing than of engineering. The Morris Minor 1000, the Morris 1100, and the Austin-Healey Sprite Mark II were all fitted with a BMC A-Series engine of the same stroke and bore according to their specifications, and were from the same maker. However the engine capacities were quoted as 1000cc, 1100cc and 1098cc respectively in the sales literature and on the vehicle badges.

Engine pollution

Generally internal combustion engines, particularly reciprocating internal combustion engines, produce moderately high pollution levels, due to incomplete combustion of carbonaceous fuel, leading to carbon monoxide and some soot along with oxides of nitrogen & sulfur and some unburnt hydrocarbons depending on the operating conditions and the fuel/air ratio. The primary causes of this are the need to operate near the stoichiometric ratio for petrol engines in order to achieve combustion (the fuel would burn more completely in excess air) and the "quench" of the flame by the relatively cool cylinder walls.

Diesel engines produce a wide range of pollutants including aerosols of many small particles (PM10) that are believed to penetrate deeply into human lungs. Engines running on liquified petroleum gas (LPG) are very low in emissions as LPG burns very clean and complete and does not contain sulphur or lead.

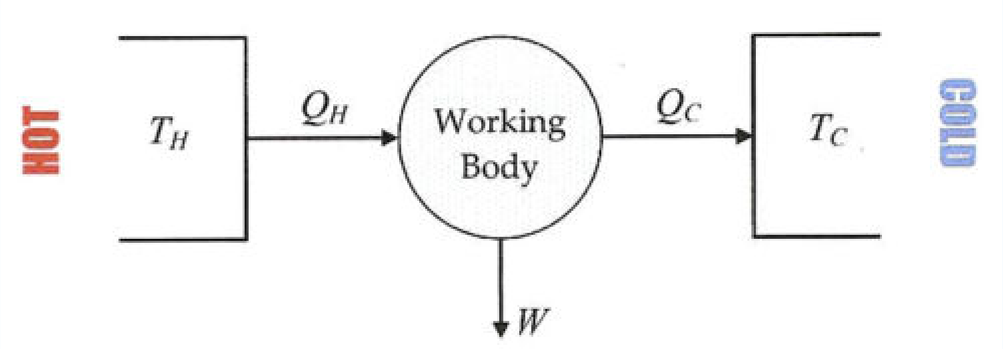
- Many fuels contain sulfur leading to sulfur oxides (SOx) in the exhaust, promoting acid rain.
- The high temperature of combustion creates greater proportions of nitrogen oxides (NOx), demonstrated to be hazardous to both plant and animal health.
- Net carbon dioxide production is not a necessary feature of engines, but since most engines are run from fossil fuels this usually occurs. If engines are run from

biomass, then no net carbon dioxide is produced as the growing plants absorb as much, or more carbon dioxide while growing.

- Hydrogen engines need only produce water, but when air is used as the oxidizer nitrogen oxides are also produced.

Heat engine

In engineering and thermodynamics, a **heat engine** performs the conversion of heat energy to mechanical work by exploiting the temperature gradient between a hot "source" and a cold "sink". Heat is transferred from the source, through the "working body" of the engine, to the sink, and in this process some of the heat is converted into work by exploiting the properties of a working substance (usually a gas or liquid).



Heat engine diagram

Overview

In general terms, the larger the difference in temperature between the hot source and the cold sink, the larger is the potential efficiency of the cycle. On Earth, the cold side of any heat engine is limited to close to the ambient temperature of the environment, or not much lower than 300 Kelvin, so most efforts to improve the thermodynamic efficiencies of various heat engines focus on increasing the temperature of the source, within material limits.

The efficiency of various heat engines proposed or used today ranges from 3 percent(97 percent waste heat) for the OTEC ocean power proposal through 25 percent for most automotive engines, to 35 percent for a supercritical coal plant, to about 60 percent for a steam-cooled combined cycle gas turbine. All of these processes gain their efficiency (or lack thereof) due to the temperature drop across them.

OTEC uses the temperature difference of ocean water on the surface and ocean water from the depths, a small difference of perhaps 25 degrees celsius, and so the efficiency must be low. The combined cycle gas turbines use natural-gas fired burners to heat air to near 1530 degrees celsius, a difference of a large 1500 degrees, and so the efficiency can be large when the steam-cooling cycle is added in.

Everyday examples

Examples of everyday heat engines include: the steam engine, the diesel engine, and the gasoline (petrol) engine in an automobile. A common toy that is also a heat engine is a drinking bird. All of these familiar heat engines are powered by the expansion of heated gases. The general surroundings are the heat sink, providing relatively cool gases which, when heated, expand rapidly to drive the mechanical motion of the engine.

Examples of heat engines

Phase change cycles

In these cycles and engines, the working fluids are gases and liquids. The engine converts the working fluid from a gas to a liquid.

- Rankine cycle (classical steam engine)
- Regenerative cycle (more efficient than Rankine cycle)
- Drinking bird cycle
- Frost heaving - water changing from ice to liquid and back again can lift rock up to 60m.

Gas only cycles

In these cycles and engines the working fluid are always like gas:

- Carnot cycle (Carnot heat engine)
- Brayton cycle or Joule cycle (Gas turbine)
- Ericsson Cycle
- Stirling cycle (Stirling engine, Thermoacoustic devices)
- Internal combustion engine (ICE):
    - Otto cycle (eg. Gasoline/Petrol engine, high-speed diesel engine)
    - Diesel cycle (eg. low-speed diesel engine)
    - Atkinson Cycle
    - Lenoir cycle (eg pulse jet engine)

    - Miller cycle

Electron cycles

- Thermoelectric (Peltier-Seebeck effect)
- thermionic emission
- Thermotunnel cooling

Magnetic cycles

- Thermo-magnetic motor (Tesla)

Cycles used for refrigeration

A refrigerator is a heat pump: a heat engine in reverse. Work is used to create a heat differential.

- Vapor-compression refrigeration
- Stirling cryocooler
- Gas-absorption refrigerator
- Air cycle machine
- Vuilleumier refrigeration

Efficiency

The efficiency of a heat engine relates how much useful power is output for a given amount of heat energy input.

From the laws of thermodynamics:

$$dW = dQ_c - (-dQ_h)$$

where
$dW = -PdV$ is the work extracted from the engine. (It is negative since work is *done by* the engine.)
$dQ_h = T_h dS_h$ is the heat energy taken from the high temperature system .(It is negative since heat is extracted from the source, hence $(-dQ_h)$ is positive.)
$dQ_c = T_c dS_c$ is the heat energy delivered to the cold temperature system. (It is positive since heat is added to the sink.)

In other words, a heat engine absorbs heat energy from the high temperature heat source, converting part of it to useful work and delivering the rest to the cold temperature heat sink.

In general, the efficiency of a given heat transfer process (whether it be a refrigerator, a heat pump or an engine) is defined informally by the ratio of "what you get" to "what you put in."

In the case of an engine, one desires to extract work and puts in a heat transfer.

$$\eta = \frac{-dW}{-dQ_h} = \frac{-dQ_h - dQ_c}{-dQ_h} = 1 - \frac{dQ_c}{-dQ_h}$$

The *theoretical* maximum efficiency of any heat engine depends only on the temperatures it operates between. This efficiency is usually derived using an ideal imaginary heat engine such as the Carnot heat engine, although other engines using different cycles can also attain maximum efficiency. Mathematically, this is due to the fact that in reversible processes, the change in entropy of the cold reservoir is the negative of that of the hot reservoir (i.e., $dS_c = -dS_h$), keeping the overall change of entropy zero. Thus:

$$\eta_{max} = 1 - \frac{T_c dS_c}{-T_h dS_h} \equiv 1 - \frac{T_c}{T_h}$$

where T_h is the absolute temperature of the hot source and T_c that of the cold sink, usually measured in kelvins. Note that dS_c is positive while dS_h is negative; in any reversible work-extracting process, entropy is overall not increased, but rather is moved from a hot (high-entropy) system to a cold (low-entropy one), decreasing the entropy of the heat source and increasing that of the heat sink.

The reasoning behind this being the **maximal** efficiency goes as follows. It is first assumed that if a more efficient heat engine than a Carnot engine is possible, then it could be driven in reverse as a heat pump. Mathematical analysis can be used to show that this assumed combination would result in a net decrease in entropy. Since, by the second law of thermodynamics, this is forbidden, the Carnot efficiency is a theoretical upper bound on the efficiency of *any* process.

Empirically, no engine has ever been shown to run at a greater efficiency than a Carnot cycle heat engine.

Other criteria of heat engine performance

One problem with the ideal Carnot efficiency as a criterion of heat engine performance is the fact that by its nature, any maximally-efficient Carnot cycle must operate at an infinitesimal temperature gradient. This is due to the fact that *any* transfer of heat between two bodies at differing temperatures is irreversible, and therefore the Carnot efficiency expression only applies in the infinitesimal limit. The major problem with that is that the object of most heat engines is to output some sort of power, and infinitesimal power is usually not what is being sought.

A much more accurate measure of heat engine efficiency is given by the **endoreversible process**, which is identical to the Carnot cycle except in that the two processes of heat transfer are *not* treated as reversible. As derived in Callen (1985), the efficiency for such a process is given by:

$$\eta = 1 - \sqrt{\frac{T_c}{T_h}}$$

The accuracy of this model can be seen in the following table (Callen):

Efficiencies of Power Plants

Power Plant	**T_c (°C)**	**T_h (°C)**	**η (Carnot)**	**η (Endoreversible)**	**η (Observed)**
West Thurrock (UK) coal-fired power plant	25	565	0.64	0.40	0.36
CANDU (Canada) nuclear power plant	25	300	0.48	0.28	0.30
Larderello (Italy) geothermal	80	250	0.33	0.178	0.16

power plant					

As shown, the endoreversible efficiency much more closely models the observed data.

Heat Engine Enhancements

Engineers have studied the various heat engine cycles extensively in an effort to improve the amount of usable work they could extract from a given power source. The Carnot Cycle limit cannot be reached with any gas-based cycle, but engineers have worked out at least two ways to possibly go around that limit, and one way to get better efficiency without bending any rules.

1) Increase the temperature difference in the heat engine. The simplest way to do this is to increase the hot side temperature, and is the approach used in modern combined-cycle gas turbines. Unfortunately, NOx production and material limits (melting the turbine blades) place a hard limit to how hot you can make a workable heat engine. Modern gas turbines are about as hot as they can become and still maintain acceptable NOx pollution levels. Another way of increasing efficiency is to lower the output temperature. Once new method of doing so is to use mixed chemical working fluids, and then exploit the changing behavior of the mixtures. One of the most famous is the so-called Kalina Cycle, which uses a 70/30 mix of ammonia and water as its working fluid. This mixture allows the cycle to generate useful power at considerably lower temperatures than most other processes.

2) Exploit the physical properties of the working fluid. The most common such exploit is the use of water above the so-called critical point, or so-called supercritical steam. The behavior of fluids above their critical point changes radically, and with materials such as water and carbon dioxide it is possible to exploit those changes in behavior to extract greater thermodynamic efficiency from the heat engine, even if it is using a fairly conventional Brayton or Rankine cycle. A newer and very promising material for such applications is CO_2. SO_2 and xenon have also been considered for such applications, although SO_2 is a little toxic for most.

3) Exploit the chemical properties of the working fluid. A fairly new and novel exploit is to use exotic working fluids with advantageous chemical properties. One such is nitrogen dioxide (NO_2), a toxic component of smog, which has a natural dimer as di-nitrogen

tetraoxide (N_2O_4). At low temperature, the N_2O_4 is compressed and then heated. The increasing temperature causes each N_2O_4 to break apart into two NO_2 molecules. This lowers the molecular weight of the working fluid, which drastically increases the efficiency of the cycle. Once the NO_2 has expanded through the turbine, it is cooled by the heat sink, which causes it to recombine into N_2O_4. This is then fed back to the compressor for another cycle. Such species as aluminum bromide (Al_2Br_6), NOCl, and Ga_2I_6 have all been investigated for such uses. To date, their drawbacks have not warranted their use, despite the efficiency gains that can be realized.

Heat engine processes

Cycle/Process	Compression	Heat Addition	Expansion	Heat Rejection
Carnot	adiabatic	isothermal	adiabatic	isothermal
Otto (Petrol)	adiabatic	isometric	adiabatic	isometric
Diesel	adiabatic	isobaric	adiabatic	isometric
Brayton (Jet)	adiabatic	isobaric	adiabatic	isobaric
Stirling	isothermal	isometric	isothermal	isometric
Ericsson	isothermal	isobaric	isothermal	isobaric

Each process is one of the following:

- isothermal (at constant temperature, maintained with heat added or removed from a heat source or sink)
- isobaric (at constant pressure)
- isometric/isochoric (at constant volume)
- adiabatic (no heat is added or removed from the working fluid)

Engineering

Engineering is the application of scientific and mathematical principles to develop economical solutions to technical problems, creating products, facilities, and structures that are useful to people. One who practices engineering is called an **engineer**, and those licensed to do so have formal designations such as Professional Engineer. Engineers use imagination, judgment, and reasoning to apply science, technology, mathematics, and practical experience. The result is the design, production, and operation of useful objects or processes. The broad discipline of engineering encompasses a range of specialized subdisciplines that focus on the issues associated with developing a specific kind of product, or using a specific type of technology.

Methodology

The crucial and unique task of the engineer is to identify, understand, and integrate the constraints on a design in order to produce a successful result. It is usually not enough to build a technically successful product; it must also meet further requirements. Constraints may include available resources, physical or technical limitations, flexibility for future modifications and additions, and other factors, such as requirements for cost, marketability, producibility, and serviceability. By understanding the constraints, engineers derive specifications for the limits within which a viable object or system may be produced and operated.

Problem solving

Engineers use their knowledge of science, mathematics, and appropriate experience to find suitable solutions to a problem. Creating an appropriate mathematical model of a problem allows them to analyze it (sometimes definitively), and to test potential solutions. Usually multiple reasonable solutions exist, so engineers must evaluate the different design choices on their merits and choose the solution that best meets their requirements. Genrich Altshuller, after gathering statistics on a large number of patents, suggested that compromises are at the heart of "low-level" engineering designs, while at a higher level the best design is one which eliminates the core contradiction causing the problem.

Engineers typically attempt to predict how well their designs will perform to their specifications prior to full-scale production. They use, among other things: prototypes, scale models, simulations, destructive tests, nondestructive tests, and stress tests. Testing ensures that products will perform as expected. Engineers as professionals take seriously their responsibility to produce designs that will perform as expected and will not cause unintended harm to the public at large. Engineers typically include a factor of safety in their designs to reduce the risk of unexpected failure. However, the greater the safety factor, the less efficient the design may be.

Computer use

As with all modern scientific and technological endeavours, computers and software play an increasingly important role. Numerical methods and simulations can help predict design performance more accurately than previous approximations.

Using computer-aided design (CAD) software, engineers are able to more easily create drawings and models of their designs. Computer models of designs can be checked for flaws without having to make expensive and time-consuming prototypes. The computer can automatically translate some models to instructions suitable for automatic machinery (e.g., CNC) to fabricate (part of) a design. The computer also allows increased reuse of previously developed designs, by presenting an engineer with a library of predefined parts ready to be used in designs. Computers can also be used as part of the manufacturing process, controlling the machines and ensuring a constant level of quality and similarity in the products. This process is Computer Aided Manufacture (CAM) and works in a similar way to CNC but where CNC controls the machinery, CAM controls the whole manufacture process from cutting to assembly.

Of late, the use of finite element method analysis (FEM analysis or FEA) software to study stress, temperature, flow as well as electromagnetic fields has gained importance. In addition, a variety of software is available to analyse dynamic systems.

Electronics engineers make use of a variety of circuit schematics software to aid in the creation of circuit designs that perform an electronic task when used for a printed circuit board (PCB) or a computer chip.

The application of computers in the area of engineering of goods is known as Product Lifecycle Management (PLM).

Etymology

The Oxford English Dictionary gives one, now obsolete, meaning of engineer (dating from 1325) as "A constructor of military engines". Engineering was originally divided into military engineering (which included construction of fortifications as well as military engines) and civil engineering (non-military construction of such as bridges).

The words *engine* and *engineer* (as well as *ingenious*) developed in parallel from the Latin root *ingeniosus*, meaning "skilled". An engineer is thus implied to be a clever, practical, designer.

With the rise of engineering as a profession in the nineteenth century the term became more narrowly applied to fields in which mathematics and science were applied to these ends. In some other languages, such as Arabic, the word for "engineering" also means "geometry".

In the nineteenth century in addition to military and civil engineering the fields then known as the mechanic arts became incorporated into engineering.

Engineering in a social context

Engineering is a subject that ranges from large collaborations to small individual projects. Almost all engineering projects are beholden to some sort of financing agency: a company, a set of investors, or a government. The result of this is that large-scale engineering projects often lose much of their original purpose to some form of bureaucracy. The few types of engineering that are minimally constrained by such issues are pro bono engineering and open design engineering.

Cultural presence

Engineering is a well respected profession. For example, in Canada it ranks as one of the public's most trusted professions.

Sometimes engineering has been seen as a somewhat dry, uninteresting field in popular culture, and has also been thought to be the domain of nerds. For example, the cartoon character Dilbert is an engineer.

This has not always been so - most British school children in the 1950s were brought up with stirring tales of 'the Victorian Engineers', chief amongst whom where the Brunels, the Stephensons, Telford and their contemporaries.

In science fiction engineers are often portrayed as highly knowledgeable and respectable individuals who understand the overwhelming future technologies often portrayed in the genre. The *Star Trek* characters Montgomery Scott and Geordi La Forge are famous examples.

Engineers are often respected and ridiculed for their intense beliefs and interests. Perhaps because of their deep understanding of the interconnectedness of many things, engineers such as Governor John H. Sununu, New York City Mayor Michael Bloomberg and Nuclear Physicist Edward Teller, are often driven into politics to "fix things" for the public good.

Occasionally, engineers may be recognized by the "Iron Ring"--a stainless steel or iron ring worn on the little (fourth) finger of the dominant hand. This tradition was originally developed in Canada in the Ritual of the Calling of an Engineer as a symbol of pride and obligation for the engineering profession. Some years later this practice was adopted in the United States. Members of the US Order of the Engineer accept this ring as a pledge to uphold the proud history of engineering. A Professional Engineer's name often has the post-nominal letters PE or P.Eng.

While it appears Engineers still only need a bachelor's degree to obtain a lucrative position that receives respect from the public, in fact it is only through a life-time devotion to their field and the further advancement of their own technical knowledge that they might arrive at such a destination.

Legislation

In most modern countries, certain engineering tasks, such as the design of bridges, electric power plants, and chemical plants, must be approved by a Professional Engineer or a Chartered Engineer.

Laws protecting public health and safety mandate that a professional must provide guidance gained through education and experience. In the United States, each state tests and licenses Professional Engineers.

The federal government, however, supervises aviation through the Federal Aviation Regulations administrated by the Dept. of Transportation, Federal Aviation Administration. Designated Engineering Representatives approve data for aircraft design and repairs on behalf of the Federal Aviation Administration.

Even with strict testing and licensure, engineering disasters still occur. Therefore, the Professional Engineer or Chartered Engineer adheres to a strict code of ethics. Each engineering discipline and professional society maintains a code of ethics, which the members pledge to uphold.

In Canada the profession in each province is governed by its own engineering association. For instance, in the Province of British Columbia an engineering graduate with 5 or more years of experience in an engineering-related field will need to be certified by the Association for Professional Engineers and Geoscientists (APEGBC) in order to become a Professional Engineer.

Refer also to the Washington accord for international accreditation details of professional engineering degrees.

Comparison to other disciplines

Science

> *You see things; and you say "Why?" But I dream things that never were; and I say "Why not?" —George Bernard Shaw*
> *Scientists study the world as it is; Engineers create the world that has never been. —Theodore von Karman*

Engineering is concerned with the design of a solution to a practical problem. A scientist may ask *why* a problem arises, and proceed to research the answer to the question or actually solve the problem in his first try, perhaps creating a mathematical model of his observations. By contrast, engineers want to know *how* to solve a problem, and *how* to implement that solution. In other words, scientists attempt to *explain* phenomena, whereas engineers use any available knowledge, including that produced by science, to *construct* solutions to problems.

There is an overlap between science (fundamental and applied) and engineering. It is not uncommon for scientists to become involved in the practical application of their discoveries; thereby becoming, for the moment, engineers. Scientists may also have to complete engineering tasks, such as designing experimental apparatus or building prototypes. Conversely, in the process of developing technology engineers sometimes find themselves exploring new phenomena, thus becoming, for the moment, scientists.

However, engineering research has a character different from that of scientific research. First, it often deals with areas in which the basic physics and/or chemistry are well understood, but the problems themselves are too complex to solve in an exact manner. The purpose of engineering research is then to find approximations to the problem that can be solved. Examples are the use of numerical approximations to the Navier-Stokes equations to solve aerodynamic flow over an aircraft, or the use of Miner's rule to calculate fatigue damage . Second, engineering research employs many semi-empirical methods that are foreign to pure scientific research, one example being the method of parameter variation.

In general, it can be stated that a scientist builds in order to learn, but an engineer learns in order to build.

Other fields

There are significant parallels between engineering and medicine. Both fields are well known for their pragmatism — the solution to real world problems often requires moving forward before phenomena are completely understood in a more rigorous scientific sense and therefore experimentation and empirical knowledge is an integral part of both. Part of medicine examines the function of the human body. The human body although biological has many functions similar to a machine. The heart for example functions much like a pump, the skeleton is like a linked structure with levers etc. This similarity has led to the development of the field of biomedical engineering that utilizes concepts developed in both disciplines.

There are also close connections between the workings of engineers and artists; they are direct in some fields, for example, architecture, landscape architecture and industrial design (even to the extent that these disciplines may sometimes be included in a University's Faculty of Engineering); and indirect in others. Artistic and engineering creativity may be fundamentally connected as the case of Leonardo Da Vinci indicates.

In Political science the term *engineering* has been borrowed for the study of the subjects of Social engineering and Political engineering that deal with forming political and social structures using engineering methodology coupled with political science principles.

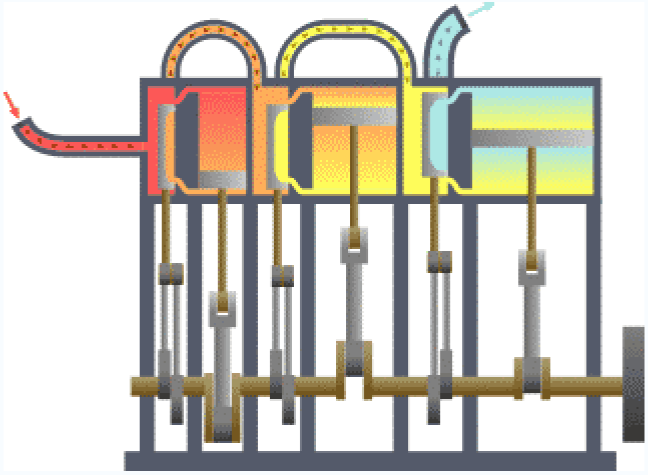
Professional and honorary organizations and societies

- National Society of Professional Engineers
- Tau Beta Pi
- Order of the Engineer

Theta Tau

Thermodynamics

Thermodynamics (from the Greek *thermos* meaning heat and *dynamics* meaning power) is a branch of physics that studies the effects of changes in temperature, pressure, and volume on physical systems at the macroscopic scale by analyzing the collective motion of their particles using statistics. Roughly, heat means "energy in transit" and dynamics relates to "movement"; thus, in essence thermodynamics studies the movement of energy and how energy instills movement. Historically, thermodynamics developed out of the need to increase the efficiency of early steam engines.



Typical **thermodynamic system** - heat moves from hot (boiler) to cold (condenser) and work is extracted.

Overview

The starting point for most thermodynamic considerations are the laws of thermodynamics, which postulate that energy can be exchanged between physical systems as heat or work. They also postulate the existence of a quantity named entropy, which can be defined for any system. In thermodynamics, interactions between large ensembles of objects are studied and categorized. Central to this are the concepts of *system* and *surroundings*. A system is composed of particles, whose average motions define its properties, which in turn are related to one another through equations of state. Properties can be combined to express internal energy and thermodynamic potentials, which are useful for determining conditions for equilibrium and spontaneous processes.

With these tools, thermodynamics describes how systems respond to changes in their surroundings. This can be applied to a wide variety of topics in science and engineering, such as engines, phase transitions, chemical reactions, transport phenomena, and even black holes. The results of thermodynamics are essential for other fields of physics and for chemistry, chemical engineering, cell biology, biomedical engineering, and materials science to name a few.

History

Sadi Carnot (1796-1832): the "father" of thermodynamics

History of thermodynamics

A short history of thermodynamics begins with the German scientist Otto von Guericke who in 1650 built and designed the world's first vacuum pump and created the world's first ever vacuum known as the Magdeburg hemispheres. He was driven to make a vacuum in order to disprove Aristotle's long-held supposition that 'Nature abhors a vacuum'. Shortly thereafter, Irish physicist and chemist Robert Boyle had learned of Guericke's designs and in 1656, in coordination with English scientist Robert Hooke, built an air pump. Using this pump, Boyle and Hooke noticed the pressure-temperature-volume correlation. In time, the ideal gas law was formulated. Then, in 1679, based on these concepts, an associate of Boyle's named Denis Papin built a bone digester, which was a closed vessel with a tightly fitting lid that confined steam until a high pressure was generated.

Later designs implemented a steam release valve to keep the machine from exploding. By watching the valve rhythmically move up and down, Papin conceived of the idea of a piston and cylinder engine. He did not however follow through with his design.

Nevertheless, in 1697, based on Papin's designs, engineer Thomas Savery built the first engine. Although these early engines were crude and inefficient, they attracted the attention of the leading scientists of the time. One such scientist was Sadi Carnot, the "father of thermodynamics", who in 1824 published *“Reflections on the Motive Power of Fire”*, a discourse on heat, power, and engine efficiency. The paper outlined the basic energetic relations between the Carnot engine, the Carnot cycle, and Motive power. This marks the start of thermodynamics as a modern science.

The term *thermodynamics* was coined by James Joule in 1858 to designate the science of relations between heat and power. By 1849, "thermo-dynamics", as a functional term, was used in William Thomson's paper *An Account of Carnot's Theory of the Motive Power of Heat.* The first thermodynamic textbook was written in 1859 by William Rankine, a civil and mechanical engineering professor at the University of Glasgow.

Classical thermodynamics

Classical thermodynamics

Classical thermodynamics is the original early 1800s variation of thermodynamics concerned with thermodynamic states, and properties as energy, work, and heat, and with the laws of thermodynamics, all lacking an atomic interpretation. In precursory form, classical thermodynamics derives from physicist Robert Boyle’s 1662 postulate that the pressure P of a given quantity of gas varies inversely as its volume V at constant temperature; i.e. in equation form: $PV = k$, a constant. From here, a semblance of a thermo-science began to develop with the construction of the first successful atmospheric steam engines in England by Thomas Savery in 1697 and Thomas Newcomen in 1712. The first and second laws of thermodynamics emerged simultaneously in the 1850s, primarily out of the works of William Rankine, Rudolf Clausius, and William Thomson (Lord Kelvin).

Statistical thermodynamics

Statistical thermodynamics

With the development of atomic and molecular theories in the late 19th century, thermodynamics was given a molecular interpretation. This field is called **statistical thermodynamics**, which can be thought of as a bridge between macroscopic and microscopic properties of systems. Essentially, statistical thermodynamics is an approach to thermodynamics situated upon statistical mechanics, which focuses on the derivation of macroscopic results from first principles. It can be opposed to its historical predecessor phenomenological thermodynamics, which gives scientific descriptions of phenomena with avoidance of microscopic details. The statistical approach is to derive all macroscopic properties (temperature, volume, pressure, energy, entropy, etc.) from the properties of moving constituent particles and the interactions between them (including quantum phenomena). It was found to be very successful and thus is commonly used.

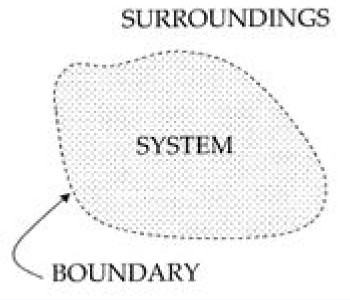
Chemical thermodynamics

Chemical thermodynamics

Chemical thermodynamics is the study of the interrelation of heat with chemical reactions or with a physical change of state within the confines of the laws of thermodynamics. During the years 1873-76 the American mathematical physicist Willard Gibbs published a series of three papers, the most famous being *On the Equilibrium of Heterogeneous Substances*, in which he showed how thermodynamic processes could be graphically analyzed, by studying the energy, entropy, volume, temperature and pressure of the thermodynamic system, in such a manner to determine if a process would occur spontaneously. During the early 20th century, chemists such as Gilbert Lewis, Merle Randall, and E. A. Guggenheim began to apply the mathematical methods of Gibbs to the analysis of chemical processes.

Thermodynamic systems

System (thermodynamics)



An important concept in thermodynamics is the “system”. A system is the region of the universe under study. A system is separated from the remainder of the universe by a boundary which may be imaginary or not, but which by convention delimits a finite volume. The possible exchanges of work, heat, or matter between the system and the surroundings take place across this boundary. There are five dominant classes of systems:

1. *Isolated Systems* – matter and energy may not cross the boundary.
2. *Adiabatic Systems* – heat may not cross the boundary.
3. *Diathermic Systems* - heat may cross boundary.
4. *Closed Systems* – matter may not cross the boundary.
5. *Open Systems* – heat, work, and matter may cross the boundary.

For isolated systems, as time goes by, internal differences in the system tend to even out; pressures and temperatures tend to equalize, as do density differences. A system in which all equalizing processes have gone practically to completion, is considered to be in a state of thermodynamic equilibrium.

In thermodynamic equilibrium, a system's properties are, by definition, unchanging in time. Systems in equilibrium are much simpler and easier to understand than systems which are not in equilibrium. Often, when analyzing a thermodynamic process, it can be assumed that each intermediate state in the process is at equilibrium. This will also considerably simplify the situation. Thermodynamic processes which develop so slowly as to allow each intermediate step to be an equilibrium state are said to be reversible processes.

Thermodynamic parameters

Conjugate variables (thermodynamics)

The central concept of thermodynamics is that of energy, the ability to do work. As stipulated by the first law, the total energy of the system and its surroundings is conserved. It may be transferred into a body by heating, compression, or addition of matter, and extracted from a body either by cooling, expansion, or extraction of matter. For comparison, in mechanics, energy transfer results from a force which causes displacement, the product of the two being the amount of energy transferred. In a similar way, thermodynamic systems can be thought of as transferring energy as the result of a generalized force causing a generalized displacement, with the product of the two being the amount of energy transferred. These thermodynamic force-displacement pairs are known as conjugate variables. The most common conjugate thermodynamic variables are pressure-volume (mechanical parameters), temperature-entropy (thermal parameters), and chemical potential-particle number (material parameters).

Thermodynamic instruments

Thermodynamic instruments

There are two types of thermodynamic instruments, the **meter** and the **reservoir**. A thermodynamic meter is any device which measures any parameter of a thermodynamic system. In some cases, the thermodynamic parameter is actually defined in terms of an idealized measuring instrument. For example, the zeroth law states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other. This principle, as noted by James Maxwell in 1872, asserts that it is possible to measure temperature. An idealized thermometer is a sample of an ideal gas at constant pressure. From the ideal gas law $PV=nRT$, the volume of such a sample can be used as an indicator of temperature; in this manner it defines temperature. Although pressure is defined mechanically, a pressure-measuring device, called a barometer may also be constructed from a sample of an ideal gas held at a constant temperature. A calorimeter is a device which is used to measure and define the internal energy of a system.

A thermodynamic reservoir is a system which is so large that it does not appreciably alter its state parameters when brought into contact with the test system. It is used to impose a particular value of a state parameter upon the system. For example, a pressure reservoir is a system at a particular pressure, which imposes that pressure upon any test system that it is mechanically connected to. The earth's atmosphere is often used as a pressure reservoir.

It is important that these two types of instruments are distinct. A meter does not perform its task accurately if it behaves like a reservoir of the state variable it is trying to measure. If, for example, a thermometer, were to act as a temperature reservoir it would alter the temperature of the system being measured, and the reading would be incorrect. Ideal meters have no effect on the state variables of the system they are measuring.

Thermodynamic states

Thermodynamic state

When a system is at equilibrium under a given set of conditions, it is said to be in a definite *state*. The state of the system can be described by a number of intensive variables and extensive variables. The properties of the system can be described by an equation of state which specifies the relationship between these variables. State may be thought of as the instantaneous quantitative description of a system with a set number of variables held constant.

Thermodynamic processes

Thermodynamic processes

A **thermodynamic process** may be defined as the energetic evolution of a thermodynamic system proceeding from an initial state to a final state. Typically, each thermodynamic process is distinguished from other processes, in energetic character, according to what parameters, as temperature, pressure, or volume, etc., are held fixed. Furthermore, it is useful to group these processes into pairs, in which each variable held constant is one member of a conjugate pair. The six most common thermodynamic processes are shown below:

1. An isobaric process occurs at constant pressure.
2. An isochoric process, or *isometric/isovolumetric process*, occurs at constant volume.
3. An isothermal process occurs at a constant temperature.
4. An isentropic process occurs at a constant entropy.
5. An isenthalpic process occurs at a constant enthalpy.
6. An adiabatic process occurs without loss or gain of heat.

The laws of thermodynamics

Laws of thermodynamics

In thermodynamics, there are four laws of very general validity, and as such they do not depend on the details of the interactions or the systems being studied. Hence, they can be applied to systems about which one knows nothing other than the balance of energy and matter transfer. Examples of this include Einstein's prediction of spontaneous emission around the turn of the 20th century and current research into the thermodynamics of black holes.

The four laws are:

- Zeroth law of thermodynamics, stating that thermodynamic equilibrium is an equivalence relation.

  If two thermodynamic systems are in thermal equilibrium with a third, they are also in thermal equilibrium with each other.

- First law of thermodynamics, about the conservation of energy

  The increase in the energy of a closed system is equal to the amount of energy added to the system by heating, minus the amount lost in the form of work done by the system on its surroundings.

- Second law of thermodynamics, about entropy

  The total entropy of any isolated thermodynamic system tends to increase over time, approaching a maximum value.

- Third law of thermodynamics, about absolute zero temperature

  As a system asymptotically approaches absolute zero of temperature all processes virtually cease and the entropy of the system asymptotically approaches a minimum value.
  This law is more clearly stated as: "the entropy of a perfectly crystalline body at absolute zero temperature is zero."

Thermodynamic potentials

Thermodynamic potentials

As can be derived from the energy balance equation on a thermodynamic system there exist energetic quantities called thermodynamic potentials, being the quantitative measure of the stored energy in the system. The four most well known potentials are:

Internal energy	U

Helmholtz free energy	$A = U - TS$
Enthalpy	$H = U + PV$
Gibbs free energy	$G = U + PV - TS$

Potentials are used to measure energy changes in systems as they evolve from an initial state to a final state. The potential used depends on the constraints of the system, such as constant temperature or pressure. Internal energy is the internal energy of the system, enthalpy is the internal energy of the system plus the energy related to pressure-volume work, and Helmholtz and Gibbs free energy are the energies available in a system to do useful work when the temperature and volume or the pressure and temperature are fixed, respectively.

Mechanical work

Mechanical work is a force applied through a distance, defined mathematically as the line integral of a scalar product of force and displacement vectors. Work is a scalar quantity which can be positive or negative.

As seen from the above definition, force can do positive, negative, or zero work. For instance, a centripetal force in uniform circular motion does zero work (because the scalar product of force and displacement vector is zero as they are orthogonal to each other). Another example is Lorentz magnetic force on moving electric charge which always does zero work because it is always orthogonal to the direction of motion of the charge.

Definition

Note: Readers not familiar with multivariate calculus or vectors, please see "Simpler formulae" below.

definition 1: Work is defined as the following line integral:

$$W = \int_C \vec{F} \cdot d\vec{s}$$

where:

C is the path or curve traversed by the object;
$\vec{F}$ is the force vector;
$\vec{s}$ is the position vector.

This formula readily explains how a nonzero force can do zero work. The simplest case is where the force is always perpendicular to the direction of motion, making the integrand always zero (viz. circular motion). However, even if the integrand sometimes takes nonzero values, it can still integrate to zero if it is sometimes negative and sometimes positive.

The possibility of a nonzero force doing zero work exemplifies the difference between work and a related quantity: impulse (the integral of force over time). Impulse measures change in a body's momentum, a vector quantity sensitive to direction, whereas work considers only the magnitude of the velocity. For instance, as an object in uniform circular motion traverses half of a revolution, its centripetal force does no work, but it transfers a nonzero impulse.

Units

work (thermodynamics)

The SI derived unit of work is the joule (J), which is defined as the work done by a force of one newton acting over a distance of one meter. This definition is based on Sadi Carnot's 1824 definition of work as "weight *lifted* through a height", which is based on the fact that early steam engines were principally used to lift buckets of water, though a gravitational height, out of flooded ore mines. The dimensionally equivalent newton-meter (N·m) is sometimes used instead; however, it is also sometimes reserved for torque to distinguish its units from work or energy.

Non-SI units of work include the erg, the foot-pound, the foot-poundal, and the liter-atmosphere.

Simpler formulae

In the simplest case, that of a body moving in a steady direction, and acted on by a constant force parallel to that direction, the work is given by the formula

$$W = FD$$

where

F is the force and
D is the distance travelled by the object.

The work is taken to be negative when the force opposes the motion. More generally, the force and distance are taken to be vector quantities, and combined using the dot product:

$$W = \vec{F} \cdot \vec{\mathbf{D}} = |\mathbf{F}||\mathbf{D}| \cos \phi$$

where φ is the angle between the force and the displacement vector. This formula holds true even when the object changes its direction of travel throughout the motion.

To further generalize the formula to situations in which the force changes over time, it is necessary to use differentials to express the infinitesimal work done by the force over an infinitesimal displacement, thus:

$$dW = \vec{F} \cdot d\vec{s}$$

The integration of both sides of this equation yields the most general formula, as given above.

Types of work

Forms of work that are not evidently mechanical in fact represent special cases of this principle. For instance, in the case of "electrical work", an electric field does work on charged particles as they move through a medium.

One mechanism of heat conduction is collisions between fast-moving atoms in a warm body with slow-moving atoms in a cold body. Although colliding atoms do work on each other, it averages to nearly zero in bulk, so conduction is not considered to be mechanical work.

PV work

Chemical thermodynamics studies *PV work*, which occurs when the volume of a fluid changes. PV work is represented by the following differential equation:

$$dW = -PdV$$

where:

- W = work done on the system
- P = external pressure
- V = volume

Therefore, we have:

$$W = -\int_{V_i}^{V_f} P\,dV$$

Like all work functions, PV work is path-dependent. (The path in question is a curve in the Euclidean space specified by the fluid's pressure and volume, and infinitely many such curves are possible.) From a thermodynamic perspective, this fact implies that *PV* work is not a state function. This means that the differential *dW* is an inexact differential; to be more rigorous, it should be written đW (with a line through the d).

From a mathematical point of view, that is to say, *dW* is not an exact one-form. This line through is merely a flag to warn us there is actually no function (0-form) *W* which is the potential of *dW*. If there were, indeed, this function *W*, we should be able to just use Stokes Theorem, and evaluate this putative function, the potential of *dW*, at the boundary of the path, that is, the initial and final points, and therefore the work would be a state function. This impossibility is consistent with the fact that it does not make sense to refer to *the work on a point*; work presupposes a path.

PV work is often measured in the (non-SI) units of litre-atmospheres, where 1 L·atm = 101.3 J.

Mechanical energy

Mechanical energy

The *mechanical energy* of a body is that part of its total energy which is subject to change by mechanical work. It includes kinetic energy and potential energy. Some notable forms of energy that it does not include are thermal energy (which can be increased by frictional work, but not easily decreased) and rest energy (which is constant so long as the rest mass remains the same).

The relation between work and kinetic energy

If an external work *W* acts upon a body, causing its kinetic energy to change from E_{k1} to E_{k2}, then:

$$W = \Delta E_k = E_{k2} - E_{k1}$$

Conservation of mechanical energy

The principle of *conservation of mechanical energy* states that, if a system is subject only to conservative forces (e.g. only to a gravitational force), its mechanical energy remains constant.

For instance, if an object with constant mass is in free fall, the total energy of position 1 will equal that of position 2.

$$(E_k + E_p)_1 = (E_k + E_p)_2$$

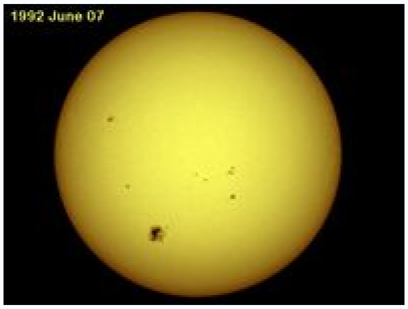
where

- E_k is the kinetic energy, and
- E_p is the potential energy.

The external work will usually be done by the friction force between the system on the motion or the internal-non conservative force in the system.

Heat

In physics, **heat**, symbolized by *Q*, is defined as *energy in transit*. Generally, heat is a form of energy transfer associated with the different motions of atoms, molecules and other particles that comprise matter when it is hot and when it is cold. High temperature bodies, which often result in high heat transfer, can be created by chemical reactions (such as burning), nuclear reactions (such as fusion taking place inside the Sun), electromagnetic dissipation (as in electric stoves), or mechanical dissipation (such as friction). Heat can be transferred between objects by radiation, conduction and convection. Temperature, defined as the measure of an object to spontaneously give up energy, is used as a measure of the internal energy or enthalpy, that is the level of elementary motion giving rise to heat transfer. Heat can only be transferred between objects, or areas within an object, with different temperatures (as given by the zeroth law of thermodynamics, and then, in the absence of work, only in the direction of the colder body (as per the second law of thermodynamics).



The photosphere of the sun is quite hot at 5800 kelvins and radiates immense amounts of visible and infrared electromagnetic radiation (blackbody radiation).

History

The first to have put forward a semblance of a theory on heat was the Greek philosopher Heraclitus who lived around 500 BC in the city of Ephesus in Ionia, Asia Minor. He became famous as the "flux and fire" philosopher for his proverbial utterance: "All things are flowing." Heraclitus argued that the three principle elements in nature were fire, earth, and water. Of these three, however, fire is assigned as the central element controlling and modifying the other two. The universe was postulated to be in a continuous state of flux or permanent condition of change as a result of transformations of fire. Heraclitus summarized his philosophy as: "All things are an exchange for fire."

As early as 460 BC Hippocrates, the father of medicine, postulated that:

> **Heat**, a quantity which functions to animate, derives from an internal fire located in the left ventricle.

The hypothesis that heat is a form of motion was proposed initially in the 12th century. Around 1600, the English philosopher and scientist Francis Bacon surmised that:

> **Heat** itself, its essence and quiddity is motion and nothing else.

This echoed the mid-17th century view of English scientist Robert Hooke, who stated:

> **heat** being nothing else but a brisk and vehement agitation of the parts of a body.

The ability to be able to use heat transfer to generate work allowed the invention and development of the steam engine by people such as Thomas Newcomen and James Watt. In addition, in 1797 a cannon manufacturer Sir Benjamin Thompson, Count Rumsford, demonstrated through the use of friction it was possible to convert work to heat. To do this, he designed a specially shaped cannon barrel, thoroughly insulated against heat loss, then replaced the sharp boring tool with a dull drill bit, and immersed the front part of the gun in a tank full of water. Using this setup, to the amazement of his onlookers, he made cold water boil in two-and-half-hours time, without the use of fire.

Several theories on the nature of heat were developed. In the 17th century, Johann Becher proposed that heat was associated with an undetectable material called phlogiston that was driven out of a substance when it was burnt. This was finally refuted by Lavosier demonstrating the importance of oxygen in burning in 1783. He proposed instead the caloric theory which saw heat as a type of weightless, invisible fluid that moved when out of equilibrium. It was this theory used in 1824 by the French engineer Sadi Carnot when he published *Reflections on the Motive Power of Fire*. He set forth the importance of heat transfer: "production of motive power is due not to an actual consumption of caloric, but to its transportation form a warm body to a cold body, i.e. to its re-establishment of equilibrium." According to Carnot, this principle applies to any machine set in motion by heat.

Another theory was the kinetic theory of gases, the basis of which was laid out in 1738 by the Swiss physician and mathematician Daniel Bernoulli in his *Hydrodynamica*. In this work, Bernoulli first proposed that gases consist of great numbers of molecules moving in all directions, that their impact on a surface causes the gas pressure that we feel. The internal energy of a substance is then the sum of the kinetic energy associated with each molecule, and heat transfer occurs from regions with energetic molecules, and so high internal energy, to those with less energetic molecules, and so lower internal energy.

The work of Joule and Mayer demonstrated that heat and work were interchangable, and led to the statement of the principle of the conservation of energy by Hermann von Helmholtz in 1847. Clausius demonstrated in 1850 that caloric theory could be reconciled with kinetic theory provided that the conservation of energy was employed rather than the movement of a substance, and stated the First Law of Thermodynamics.

Overview

Under the First Law of Thermodynamics, heat (and work) are processes that change the internal energy of a substance or object. Heat is the transfer of energy over the boundary of a system owing to a temperature gradient. The SI unit for energy is the Joule, though the British Thermal Unit is still occasionally used in the United States.

Heat emanating from a red-hot iron rod.

Heat is a process quantity, as opposed to being a state quantity, and is to thermal energy as work is to mechanical energy. Heat flows between regions that are not in thermal equilibrium with each other; it spontaneously flows from areas of high temperature to areas of low temperature. All objects (matter) have a certain samount of internal energy, a state quantity that is related to the random motion of their atoms or molecules. When two bodies of different temperature come into thermal contact, they will exchange internal energy until the temperature is equalized; that is, until they reach thermal equilibrium. The amount of energy transferred is the amount of heat exchanged. It is a common misconception to confuse heat with internal energy: heat is related to the change in internal energy and the work performed by the system. The term heat is used to describe the *flow* of energy, while the term internal energy is used to describe the energy itself.

In common usage the term *heat* denotes the warmth, or hotness, of surrounding objects and is used to mean that an object has a high temperature. The concept that warm objects "contain heat" is not uncommon, but *hot* is nearly always used as a relative term (an object is hot compared with its surroundings or those of the person using the term) so that high temperature is directly associated with high heat transfer.

The amount of heat that has to be transferred to or from an object when its temperature varies by one degree is called **heat capacity**. Heat capacity is specific to each and every object or substance. When referred to a quantity unit (such as mass or moles), the heat exchanged per degree is termed **specific heat**, and depends primarily on the composition and physical state (phase) of an object. Fuels generate predictable amounts of heat when burned; this heat is known as **heating value** and is expressed per unit of quantity. Upon changing from one phase to another, pure substances can exchange heat without their temperature suffering any change. The amount of heat exchanged during a phase change is known as **latent heat** and depends primarily on the substance and the initial and final phase.

Notation

The total amount of energy transferred through heat transfer is conventionally abbreviated as Q. The conventional sign convention is that when a body releases heat into its surroundings, $Q < 0$ (-); when a body absorbs heat from its surroundings, $Q > 0$ (+). **Heat transfer rate**, or heat flow per unit time, is denoted by:

$$\dot{Q} = \frac{dQ}{dt}.$$

It is measured in watts. **Heat flux** is defined as rate of heat transfer per unit cross-sectional area, and is denoted ***q***, resulting in units of watts per metre squared. Slightly different notation conventions can be used, which may denote heat flux as, for example, $\dot{Q}''$.

Thermodynamics

Heat is related to the internal energy U of the system and work W done by the system by the first law of thermodynamics:

$$\Delta U = Q - W$$

which means that the energy of the system can change either via work or via heat. The transfer of heat to an ideal gas at constant pressure increases the internal energy and performs boundary work (i.e. allows a control volume of gas to become larger or smaller), provided the volume is not constrained. Returning to the first law equation and separating the work term into two types, "boundary work" and "other" (e.g. shaft work performed by a compressor fan), yields the following:

$$\Delta U + W_{boundary} = Q - W_{other}$$

This combined quantity $\Delta U + W_{boundary}$ is enthalpy, H, one of the thermodynamic potentials. Both enthalpy, H, and internal energy, U are state functions. State functions return to their initial values upon completion of each cycle in cyclic processes such as that of a heat engine. In contrast, neither Q nor W are properties of a system and need not sum to zero over the steps of a cycle. The infinitesimal expression for heat, δQ, forms an inexact differential for processes involving work. However, for processes involving no change in volume, applied magnetic field, or other external parameters, δQ, forms an exact differential. Likewise, for adiabatic processes (no heat transfer), the expression for work forms an exact differential, but for processes involving transfer of heat it forms an inexact differential .

The changes in enthalpy and internal energy can be related to the heat capacity of a gas at constant pressure and volume respectively. When there is no work, the heat , Q, required to change the temperature of a gas from an initial temperature, T_0, to a final temperature, T_f depends on the relationship:

$$Q = \int_{T_0}^{T_f} C_p \, dT$$

for constant pressure, whereas at constant volume:

$$Q = \int_{T_0}^{T_f} C_v \, dT$$

For incompressible substances, such as solids and liquids, there is no distinction among the two expressions as they are nearly incompressible. Heat capacity is an extensive quantity and as such is dependent on the number of molecules in the system. It can be represented as the product of mass, *m* , and specific heat capacity, c_s according to:

$$C_p = mc_s$$

or is dependent on the number of moles and the molar heat capacity, c_n according to:

$$C_p = nc_n$$

The molar and specific heat capacities are dependent upon the internal degrees of freedom of the system and not on any external properties such as volume and number of molecules.

The specific heats of monatomic gases (e.g., helium) are nearly constant with temperature. Diatomic gases such as hydrogen display some temperature dependence, and triatomic gases (e.g., carbon dioxide) still more.

In liquids at sufficiently low temperatures, quantum effects become significant. An example is the behavior of bosons such as helium-4. For such substances, the behavior of heat capacity with temperature is discontinuous at the Bose-Einstein condensation point.

The quantum behavior of solids is adequately characterized by the Debye model. At temperatures well below the characteristic Debye temperature of a solid lattice, its specific heat will be proportional to the cube of absolute temperature. A second, smaller term is needed to complete the expresssion for low-temperature metals having conduction electrons, an example of Fermi-Dirac statistics.

Changes of phase

The boiling point of water, at sea level and normal atmospheric pressure and temperature will always be at nearly 100 °C no matter how much heat is added. The extra heat changes the phase of the water from liquid into water vapor. The heat added to change the phase of a substance in this way is said to be "hidden," and thus it is called latent heat (from the Latin *latere* meaning "to lie hidden"). Latent heat is the heat per unit mass necessary to change the state of a given substance, or:

$$L = \frac{Q}{\Delta m}$$

and

$$Q = \int_{M_0}^{M} L\, dm$$

Note that as pressure increases, the L rises slightly. Here, M_o is the amount of mass initially in the new phase, and M is the amount of mass that ends up in the new phase. Also,L generally does not depend on the amount of mass that changes phase, so the equation can normally be written:

$$Q = L\Delta m$$

Sometimes L can be time-dependent if pressure and volume are changing with time, so that the integral can be written as:

$$Q = \int L \frac{dm}{dt} dt$$

Heat transfer mechanisms

Heat transfer

As mentioned previously, heat tends to move from a high temperature region to a low temperature region. This heat transfer may occur by the mechanisms conduction and radiation. In engineering, the term *convective heat transfer* is used to describe the combined effects of conduction and fluid flow and is regarded as a third mechanism of heat transfer.

Conduction

Conduction is the most common means of heat transfer in a solid. On a microscopic scale, conduction occurs as hot, rapidly moving or vibrating atoms and molecules interact with neighboring atoms and molecules, transferring some of their energy (heat) to these neighboring atoms. In insulators the heat flux is carried almost entirely by phonon vibrations.

The "electron fluid" of a conductive metallic solid conducts nearly all of the heat flux through the solid. Phonon flux is still present, but carries less than 1% of the energy. Electrons also conduct electric current through conductive solids, and the thermal and electrical conductivities of most metals have about the same ratio. A good electrical conductor, such as copper, usually also conducts heat well. The Peltier-Seebeck effect exhibits the propensity of electrons to conduct heat through an electrically conductive solid. Thermoelectricity is caused by the relationship between electrons, heat fluxes and electrical currents.

Convection

Convection is usually the dominant form of heat transfer in liquids and gases. This is a term used to characterize the combined effects of conduction and fluid flow. In convection, enthalpy transfer occurs by the movement of hot or cold portions of the fluid together with heat transfer by conduction. For example, when water is heated on a stove, hot water from the bottom of the pan rises, heating the water at the top of the pan. Two types of convection are commonly distinguished, *free convection*, in which gravity and buoyancy forces drive the fluid movement, and *forced convection*, where a fan, stirrer, or other means is used to move the fluid. Buoyant convection is because of the effects of gravity, and hence does not occur in microgravity environments.

Radiation

Radiation is the only form of heat transfer that can occur in the absence of any form of medium and as such is the only means of heat transfer through a vacuum. Thermal radiation is a direct result of the movements of atoms and molecules in a material. Since these atoms and molecules are composed of charged particles (protons and electrons), their movements result in the emission of electromagnetic radiation, which carries energy away from the surface. At the same time, the surface is constantly bombarded by radiation from the surroundings, resulting in the transfer of energy to the surface. Since the amount of emitted radiation increases with increasing temperature, a net transfer of energy from higher temperatures to lower temperatures results.

The frequencies of the emitted photons are described by the Planck distribution. A black body at higher temperature will emit photons having a distributional peak at a higher frequency than will a colder object, and their respective spectral peaks will be separated according to Wien's displacement law. The photosphere of the Sun, at a temperature of approximately 6000 K, emits radiation principally in the visible portion of the spectrum. The solar radiation incident upon the earth's atmosphere is largely passed through to the surface. The atmosphere is largely transparent in the visible spectrum. However, in the infrared spectrum that is characteristic of a blackbody at 300K, the temperature of the earth, the atmosphere is largely opaque. The blackbody radiation from earth's surface is absorbed or scattered by the atmosphere. Though some radiation escapes into space, it is the radiation absorbed and subsequently emitted by atmospheric gases. It is this spectral selectivity of the atmosphere that is responsible for the planetary greenhouse effect.

The behavior of a common household lightbulb has a spectrum overlapping the blackbody spectra of the sun and the earth. A portion of the photons emitted by a tungsten light bulb filament at 3000K lie in the visible spectrum. However, the majority of the photonic energy is associated with longer wavelengths and will transfer heat to the environment, as can be deduced empirically by observing a household incandescent lightbulb. Whenever EM radiation is emitted and then absorbed, heat is transferred. This principle is used in microwave ovens, laser cutting, and RF hair removal.

Other heat transfer mechanisms

- Latent heat: Transfer of heat through a physical change in the medium such as water-to-ice or water-to-steam involves significant energy and is exploited in many ways: steam engine, refrigerator etc. (see latent heat of fusion)
- Heat pipe: Using latent heat and capillary action to move heat, it can carry many times as much heat as a similar sized copper rod. Originally invented for use in satellites, they are starting to have applications in personal computers.

Heat dissipation

In cold climates, houses with their heating systems form dissipative systems. In spite of efforts to insulate such houses, to reduce heat losses to their exteriors, considerable heat is lost, or dissipated, from them which can make their interiors uncomfortably cool or cold. Furthermore, the interior of the house must be maintained out of thermal equilibrium with its external surroundings for the comfort of its inhabitants. In effect domestic residences are oases of warmth in a sea of cold and the thermal gradient between the inside and outside is often quite steep. This can lead to problems such as condensation and uncomfortable draughts which, if left unaddressed, can cause structural damage to the property. This is why modern insulation techniques are required to reduce heat loss.

In such a house, a thermostat is a device capable of starting the heating system when the house's interior falls below a set temperature, and of stopping that same system when another (higher) set temperature has been achieved. Thus the thermostat controls the flow of energy into the house, that energy eventually being dissipated to the exterior.

Energy

In general, the concept of **energy** refers to "the potential for causing changes." The word is used in several different contexts. The scientific use has a precise, well-defined meaning, while the many non-scientific uses often do not.

In physics, energy is mathematically defined as a work done by a certain force (gravitational, electric, magnetic, force of inertia, etc) and usually taken with a negative sign. Due to variety of forces, energy has many different forms (usually named after specific force involved), however these can be broken down into two main forms: kinetic energy and potential energy. According to the above definition, energy has the same units as work; a force applied through a distance. The SI unit of energy, the joule, equals one newton applied through one meter, for example.

Lightning is a highly visible form of energy transfer.

Etymology

The etymology of the term is from Greek *ενέργεια*, *εν-* means "in" and *έργον* means "work"; the *-ια* suffix forms an abstract noun. The compound *εν-εργεια* in Epic Greek meant "divine action" or "magical operation"; it is later used by Aristotle in a meaning of "activity, operation" or "vigour", and by Diodorus Siculus for "force of an engine."

Historical perspective

The concept of energy, in the distant past, was used to explain easily observable phenomena, such as the effects observed on the properties of objects or any other changes. It was generally construed that all changes can in fact be explained through some sort of energy. Soon the idea, that energy could be stored in objects took its roots in scientific thought and the concept of energy came to embrace the idea of the potential for change as well as change itself. Such effects (both potential and realized) come in many different forms. While in spiritualism they were reflected in changes in a person, in physical sciences it is reflected in different forms of energy *itself*. For example, electrical energy stored in a battery, the chemical energy stored in a piece of food (along with the oxygen needed to burn it), the thermal energy of a water heater, or the kinetic energy of a moving train.

In 1807, Thomas Young was the first to use the term "energy" instead of vis viva to refer to the product of the mass of an object and its velocity squared. Gustave-Gaspard Coriolis described "kinetic energy" in 1829 in its modern sense, and in 1853, William Rankine coined the term "potential energy."

The development of steam engines required engineers to develop concepts and formulas that would allow them to describe the mechanical and thermal efficiencies of their systems. Engineers such as Sadi Carnot and James Prescott Joule, mathematicians such as Émile Claperyon and Hermann von Helmholtz , and amateurs such as Julius Robert von Mayer all contributed to the notions that the ability to perform certain tasks, called work, was somehow related to the amount of energy in the system. The nature of energy was elusive, however, and it was argued for some years whether energy was a substance (the caloric) or merely a physical quantity, such as momentum.

William Thomson (Lord Kelvin) amalgamated all of these laws into his laws of thermodynamics, which aided in the rapid development of energetic descriptions of chemical processes by Rudolf Clausius, Josiah Willard Gibbs, Walther Nernst. In addition, this allowed Ludwig Boltzmann to describe entropy in mathematical terms, and to discuss, along with Jožef Stefan, the laws of radiant energy.

During a 1961 lecture for undergraduate students at the California Institute of Technology, Richard Feynman, a celebrated physics teacher and a Nobel Laureate, had said "*There is a fact, or if you wish, a law, governing natural phenomena that are known to date. There is no known exception to this law—it is exact so far we know. The law is called conservation of energy [it states that there is a certain quantity, which we call energy that does not change in manifold changes which nature undergoes]. That is a* *most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity, which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number, and when we finish watching nature go through her tricks and calculate the number again, it is the same...*" This lecture was later published in the Volume 1 of the The Feynman Lectures on Physics.

> *Further information: Timeline of thermodynamics*
> *History of Physics*

Heat, a commonly seen form of energy, is a mixture of potential energy and kinetic energy.

Energy in Natural Sciences

The concepts of energy and its transformations are useful in explaining all natural phenomena. The Law of conservation of energy is equally useful. The direction of transformations due to energy changes is often influenced by entropy considerations. Certain forms of energy are often said to be more concentrated than others; using this terminology it can be said that in natural processes energy is transformed from more concentrated forms, to less concentrated and more randomly distributed forms, for example heat.

The exact context of various natural phenomena and transformations varies from one natural science to another. Some examples are:

Physics

> *Mechanics, Mechanical work, Thermodynamics, and Quantum mechanics*

The transformations that constitute the context of energy in physics, is the change in position or movement of an object which is brought about through the action of a force.

Thus in the context of physics, energy is said to be the ability to do work; the strict mathematical definition of energy in physics always being the amount of work itself (done by or against specified force). Because forces are usually classified by type (gravitational, electrostatic, etc), so also are the specific forms of work these forces produce (or are involved in). For example, a gravitational potential energy is defined as the amount of work to elevate (or lower) a mass against a gravitational force; electrostatic energy is defined as the work done to rearrange electric charges against electric force, kinetic energy is defined as the amount of work to accelerate a body (against force of inertia) to a given velocity, etc.

In the simplest language, work is a force multiplied by a distance (more accurately, force integrated over a certain path).

$$W = \int \mathbf{F} \cdot \mathrm{d}\mathbf{s}$$

The equation above says that the work (W) is equal to the integral of the dot product of the force ($\mathbf{F}$) on a body and the infinitesimal of the body's translation ($\mathbf{s}$).

Depending on the kind of force **F** involved, work of this force results in a change of the corresponding kind of energy (gravitational, electrostatic, kinetic, etc).

Units of energy are thus exactly the same as units of work (=joule in SI). Because work is frame dependent (= can only be defined relative to certain initial state or reference state of the system), energy also becomes frame dependent. For example, a speeding bullet has kinetic energy in the reference frame of a non-moving observer, it has zero kinetic energy in its proper (co-moving) reference frame -- because it takes zero work to accelerate a bullet from zero speed to zero speed. Of course, the selection of a reference state (or reference frame) is completely arbitrary - and usually is dictated to maximally simplify the problem to be dealt with. However, when the total energy of a system cannot be decreased by simple choice of reference frame, then the (minimal) energy remaining in the system is associated with an invariant mass of the system. In this special frame, called the center-of-momentum frame or center-of-mass frame, total energy of the system E and both its invariant mass and relativistic mass m are related by Einstein's famous equation $E = mc^2$.

The concept of quantized energy is a product of quantum mechanics. Any system can be described by an Schrodinger equation, and for bound systems the solution of this equation leads to certain permitted states, each characterized by an energy level. In the realm of wave mechanics the energy is related to the frequency of an electromagnetic radiation by the Planck equation **E = hν** (where h is the Planck's constant and **ν** the frequency)

Chemistry

> *Chemical thermodynamics, Chemical kinetics, Thermochemistry, and Photochemistry*

Atoms and molecules, the central concepts of chemistry, are made up of electrons and protons, therefore coulombic forces are at work during the rearrangement of atoms (during formation or decomposition of molecules). The energy associated with this movement of charge is what we call "chemical energy".

A chemical reaction invariably absorbs or releases heat or light. According to chemical thermodynamics a chemical transformation is possible only if so-called free energy decreases. The concept of free energy is a synthesis of energy and entropy. Free energy is a useful concept in chemistry, because energy considerations alone are not sufficient to decide the possibility of a chemical reaction. According to the second law of thermodynamics, the entropy of the universe must increase in all spontaneous processes (including chemical processes), and energy is transformed from one form to another (including from heat to any other form) so long as the second law is not violated. For example, a gas may expand and thus allow some of its heat to do work, but this is only possible because the net entropy of the universe *increases* due to the gas expansion, more than it *decreases* due to the disappearance of heat.

The concept of energy levels finds application in various kinds of spectroscopy, in which elucidation of atomic and molecular structure is based on the phenomenon of the presence of certain "lines" in absorption or emmision spectra. These **lines** (so called because they appear as linear features in dispersion spectra, such as might be produced by a prism or diffraction grating) are postulated to be due to a certain specific amount of energy involved in the transition of atoms or molecules, from one state to another.

Because a charactistic magnitude of energy is associated with a characteristic frequency (and wavelength) of light (or other electromagnetic radiation), such lines in spectra are direct clues to energetic changes which are permitted to happen only at certain energies, and not others.

The *speed* of a spontaneous chemical reaction is determined by yet another concept, the activation energy. It refers to the minimum average energy reactant molecules must have, in order to be able to produce product molecules. At a given temperature the fraction of molecules with this energy is usually proportional to the Boltzmann's population factor of $e^{-E/kT}$. and the dependence of a reaction rate on temperature and is often stated through the Arrhenius equation.

Biology

Bioenergetics, Cellular respiration, Photosynthesis, and Chemosynthesis

Sustenance of life is critically dependent on energy transformations; living organisms survive because of exchange of energy within and without. In a living organism chemical bonds are constantly broken and made to make the exchange and transformation of energy possible. These chemical bonds are most often bonds in carbohydrates, including sugars. Other chemical bonds include bonds in ATP and acetate, which in turn is derived from fats and oils. These molecules, along with oxygen, are common stores of concentrated energy for the biological processes. One can therefore assert that transformation of energy from a more to a less concentrated form is the driving force of all biological processes that are a subset of chemical processes. Molecular biology and biochemistry are essentially the making and breaking of certain chemical bonds in the molecules found in biological organisms.

As with other natural phenomena, the exchange of energy in biological organisms also increase the entropy of the universe. All energy transformations studied in biology are due to the chemical synthesis and decompositions ultimately brought about by the energy absorbed from photons in sunlight through insolation and photosynthesis. The total energy captured by photosynthesis in green plants from the solar radiation is 91 x 10^{26} joules of energy per year .

The predator-prey relationships, food chains, are in effect energy transformations within ecosystems that are studied in ecology.

Meteorology

Meteorological phenomena like wind, rain, hail, snow, lightning, tornados and hurricanes, are all a result of energy transformations brought about by solar energy on the planet Earth. It has been estimated that the average total *solar incoming radiation* (or insolation) is 342 watts per square meter incident to the summit of the atmosphere, at the equator at midday, a figure known as the Solar Constant. Although this amount varies a little each year, as a result of solar flares, prominences and the sunspot cycle. Some 34% of this is immediately reflected by the planetary albedo, as a result of clouds, snowfields, and even reflected light from water, rock or vegetation. As more energy is received in the tropics than is re-radiated, while more energy is radiated at the poles than is received, climatic homeostasis is only maintained by a transfer of energy from the tropics to the poles. This transfer of energy is what drives the winds and the ocean currents. Like biological processes, all meteorological processes involve transformation of energy from a concentrated form such as sunlight into a less concentrated form, such as far infrared radiation (i.e., heat radiation at the much smaller characteristic temperatures that occur on Earth, and thus is diffused into many photons). However, energy may be temporarily locally stored during this process, and the sudden release of such stored sources is responsible for the most dramatic processes mentioned above.

A volcano is the release of stored energy from below the surface of Earth originating in radioactive decay and gravitational sorting in the Earth's core and mantle of energies left over from its formation

Geology

Continental drift, mountain ranges, volcanos, and earthquakes are phenomena that are a result of energy transformations in the Earth's crust. Recent studies suggest that the Earth transforms about 6.18 x 10^{-12} watts per kilogram. Given the Earth's mass of about 5.97 x

10^{24} kilograms, this means that the rate of energy transformations inside the Earth is about 37 x 10^{12} watts per year.

From the study of neutrinos radiated from the Earth (see KamLAND), scientists have recently estimated that about 24 terawatts of this energy comes from radioactive decay (principally of potassium 40, thorium 232 and uranium 238) and the remaining 12.9 terawatts is from the continuous gravitational sorting of the core and mantle of the earth, energies left over from the formation of the Earth, about 4.57 billion years ago. The magnitude of both these forms of energy decline over time, and based on half-life alone, it has been estimated that the current radioactive energy of the planet represents less than 1% of that which was available at the time the planet was formed.

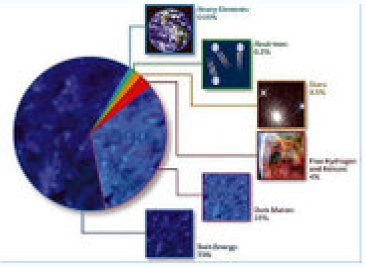
As a result, geological forces of continental accretion, subduction and sea floor spreading, account for 90% of the Earth's energy. The remaining 10% of geological tectonic energy comes through hotspots produced by mantle plumes, resulting in shield volcanoes like Hawaii, geyser activity like Yellowstone or flood basalts like Iceland.

Tectonic process, driven by heat from the Earth's interior, metamorphose weathered rocks, and during orogeny periods, lift them up into mountain ranges. The potential energy represented by the mountain range's weight and height thus represents heat from the core of the Earth which has been partly transformed into gravitational potential energy. This potential energy may be suddenly released in landslides or tsunamis. Similarly, the energy release which drives an earthquake represents stresses in rocks that are mechanical potential energy which has been similarly stored from tectonic processes.

The energy which is responsible for the geological processes of erosion and deposition is a result of the interaction of solar energy and gravity. An estimated 23% of the total insolation is used to drive the water cycle. When water vapour condenses to fall as rain, it dissolves small amounts of carbon dioxide, making a weak acid. This acid acting upon the metallic silicates that form most rocks produces chemical weathering, removing the metals, and leading to the production of rocks and sand, carried by wind and water downslope through gravity to be deposited at the edge of continents in the sea. Physical weathering of rocks is produced by the expansion of ice crystals, left by water in the joint planes of rocks. A geologic cycle is continued when these eroded rocks are later uplifted into mountains.

Astronomy and cosmology

The phenomona of stars, nova, supernova, quasars and gamma ray bursts all results of energy transformations of matter. All stellar phenomena (including of course solar activity) can be seen as driven by various kinds of energy transformations. Energy in such transformations is either from gravitational collapse of matter (usually molecular hydrogen) into various classes of astronomical objects (stars, black holes, etc.), or from nuclear fusion (of lighter elements, primarily hydrogen). Indeed all astronomical phenomena are of the most gigantic proportions of energy transformations.



Dark energy is believed to make up 70% of the universe

Light elements, primarily hydrogen and helium, are thought to have been created in the Big Bang, as per the currently accepted theories of cosmology. These light elements were spread too fast and too thinly in the Big Bang process (see nucleosynthesis) to form the most stable medium-sized atomic nuclei, like iron and nickel. This fact allows for later energy release, as such intermediate-sized elements are formed in our era. The formation of such atoms powers the energy-releasing reactions in stars.

Cosmologists are still unable to explain all cosmological phenomena purely on the basis of known conventional forms of energy (see next section) and often invoke another form called dark energy to account for certain cosmological observations.

Methods of Measurement

The methods for the measurement of energy often deploy methods for the measurement of still more fundamental concepts of science, viz. mass, distance, radiation, temperature, time, electric charge and electric current. Conventionally the technique most often employed are calorimetry, in thermodynamics that relies on the measurement of temperature: a thermometer or a bolometer for measurement of intensity of a radiation.

Forms and relations between different forms

In the context of natural sciences, energy has different forms: thermal, chemical, electrical, radiant, nuclear etc. Most of these can be reduced to kinetic energy or potential energy. Thus energy can be divided into two broad categories.

Kinetic

- Kinetic energy is defined as a work of the force accelerating a body.

- According to kinetic theory, the microscopic **kinetic energies,** ε of the particles in a gas comprise the internal energy of a system. By the equipartition theorem (which sometimes is considered as a definition of a temperature) each degree of freedom of a particle has an associated energy, $\frac{1}{2} k T$, such that the energy per particle is proportional to temperature. For a monatomic gas having N particles each with three degrees of freedom, the internal energy is:

  $$\overline{E_{kT}} = \frac{3}{2}NkT$$

  where **k** is the Boltzmann constant and **T** is absolute temperature. Whereas all internal energy is kinetic in an ideal gas, in solids half of it is stored in electromagnetic potential energy between particles. Thermal internal energy is present in all macroscopic objects in the universe. Although some heat transfer is mediated by the kinetic energy of a system's constituent particles, this kinetic energy exhibits Brownian motion, a highly disorganized state.

Electromagnetic radiation

- **Radiation energy**, also known as **light energy**, is the energy of electromagnetic radiation. Although this energy is carried by moving photons, it cannot be neatly categorized as classical kinetic energy, since photons have no invariant mass and thus the energy required to accelerate them to their velocity (and thus which is associated with their motion) cannot be calculated using other kinetic equations. However, the energy of electomagnetic radiation is associated with its momentum times its speed: **E** = **p** c. In electromagnetic radiation, the energy is carried (in equal amounts) in electric and magnetic fields. This energy is quantized, and the minimum energy associated with a given frequency or wavelength of radiation, is called a photon. The energy of a photon) is equal to: $E_{kR} = h f$ where f is the frequency of the photon and h is the Planck's constant. Photons move at the speed of light and they carry energy and momentum. Because energy or momentum can code information, photons can be used to transfer information (see fiber optics as an example).

Potential

Potential energy is stored unreleased energy (a positive quantity, like monetary savings), or else required energy (like monetary debt). This sort of energy may be positive or negative because it can represent work done *on* a system, or work done *by* a system, against a force. (Negative energy is a thus a mathematical construct in reference to another system.) For instance, using the power of a compressed spring to launch a dart uses the elastic potential energy stored within the spring. When the spring is released, this energy is converted into kinetic energy, and work is performed. There is a form of potential energy for each of the four basic forces in nature: gravity, electromagnetic, and strong and weak nuclear forces.

- **Gravitational potential energy** is the work of gravitational force during rearrangement of mutual positions of interacting masses - say, when masses are moved apart (such as when a crate is lifted), or closer together (as when a meteorite falls to Earth). If the masses of the objects are considered point masses, this work (thus the gravitational potential energy) is equal to: $E_{pG} = -\frac{GmM}{r}$ where **m** and **M** are the two masses in question, **r** is the distance between them, and **G** is the gravitational constant. In case of small displacement h << r near the Earth's surface where GM/r = g, the above formula results in the widely-used **E = mgh** approximation for gravitational potential energy.
- **Electric potential energy** is the work of electric forces during rearrangement of positions of charges, and also includes the common chemical potential energies (energy required to break chemical bonds, or obtained from forming them). The energy released in lightning, or from burning a litre of fuel oil, are common examples of electromagnetic potential energy. Quantitatively, electromagnetic potential energy is: $E_{pE} = \frac{qQ}{4\pi\epsilon_0 r}$ where **q** and **Q** are the electric charges on the objects in question, **r** is the distance between them, and **ε_0** is the electric constant of a vacuum.

- Energy can also be stored in a magnetic field. Such fields are intrinsic properties of certain particles, but they also often result from relative motion of electric charges in an electrical current; for example, superconducting magnetic energy storage works via the mechanism of **magnetic potential energy**. Magnetic potential energy is closely related to electric potential energy, since both types of potential are mediated by the electromagnetic field. High power application of magnetic potential energy is perhaps most familar as the type of energy storage which allows transfer of power within an electrical transformer.
- **Potential thermal energy** is made up of kinetic energy and electric potential energy. The potential electrical part of thermal energy is stored in "deformation" of atomic bonds during thermal motion of atoms (as atoms oscillate around their position of equilibrium, they not only have kinetic energy of motion but also a potential energy of displacement from equilibrium). This energy is a significant portion (about half) of thermal energy for strongly-bonded systems (=solids and liquids), with the rest of thermal energy being the kinetic energy of the atoms. However, the potential part of thermal energy is a smaller fraction of thermal energy in gasses.
- **Potential chemical energy** is the energy which may potentially be liberated, when the bonds of chemical structures are rearranged. Energy is never stored in chemical bonds except as a negative quantity (i.e., it always requires energy to break a bond), but net energy may be released when weak chemical bonds are broken so that stonger bonds can be made. The mixture of a fuel and oxygen is an example: this stores chemical energy **as compared to** the products of combustion, i.e., the energy is not stored in the fuel, but rather exists as a potential energy to be converted to heat when the fuel combines with oxygen. Other common examples of chemical potential are a rechargable battery, or a food item (where again the energy is not stored in the item itself, but actually in the system of *item-plus-oxygen*). Some chemical fuels or explosives (for example, nitroglycerine) do not require a second reactant substance to release potential energy, but even in these cases, the energy released does not come from the bonds of the molecule, but rather is released from the stronger bonds of the products into which it decomposes (in the case of nitroglycerine, from the powerful bond in the new N_2 produced when it explodes).
- **Potential elastic energy** is the energy stored in the elastic nature of objects. Elastic energy is actually of several types: it is sometimes a kind of electric potential energy (as in metal springs), and in these cases energy is released as

charged atoms which have been compressed are allowed to move appart. However, in other cases (such as compressed ideal gasses or rubber bands) the potential energy is not stored as electrical potential, but rather is stored as a low-entropy arrangement of atoms which can allow rapid conversion of thermal energy into work, when they are rearranged into higher-entropy structures.

In the ideal case of a metal spring described by Hooke's Law, the stored elastic energy is equal to: $E_{pE} = \frac{1}{2}kx^2$ where **k** is the spring constant, dependent on the individual spring, and **x** is the deformation of the object.

- **Nuclear potential energy**, along with electric potential energy, provides the energy released from nuclear fission and nuclear fusion processes. In both cases strong nuclear forces bind nuclear particles more strongly and closely, after the reaction has completed. Weak nuclear forces (different from strong forces) provide the potential energy for certain kinds of radioactive decay, such as beta decay. Ultimately, the energy released in nuclear processes is so large that the change in mass is appreciable as being several parts per thousand in mass: $E = \Delta mc^2$ where **Δm** is the amount of rest mass released into the surroundings as active energy (heat, light, kinetic energy), and **c** is the speed of light in a vacuum. Nuclear particles like protons and neutrons are not destroyed in fission and fusion processes, but collections of them have less mass than if they were individually free, and this mass difference is liberated as heat and radiation in nuclear reactions (the heat and radiation have the missing mass, but it often escapes from the system, where it is not measured). The energy from the Sun, also called solar energy, is an example of this form of energy conversion. In the Sun, the process of hydrogen fusion converts about 4 million metric tons of solar matter per second into to light, which is radiated into space.

Conservation of energy

conservation of energy

Energy is subject to the *law of conservation of energy*. According to this law it can neither be created (produced) nor destroyed. It can only be transformed.

During any energy transformation in (macroscopic) system, some energy is converted into incoherent microscopic motion of parts of the system: heat or thermal motion). An increase in entropy of the system often accompanies an energy transformation. Due to mathematical impossibility to invert this process (see statistical mechanics), the efficiency of energy conversion in a macroscopic system is always less than 100%.

The first law of thermodynamics states that the total inflow of energy into a system must equal the total outflow of energy from the system, plus the change in the energy contained within the system. In other words, energy is neither created nor destroyed, only converted between forms. This law is used in all branches of physics, but frequently violated for short enough periods of time during which energy can not be mathematically defined yet (see quantum electrodynamics and off shell concept). Noether's theorem relates the conservation of energy to the *time invariance* of physical laws.

The law of conservation of energy, a fundamental principle of physics, follows from the translational symmetry of time, a property of most phenomena below the cosmic scale that makes them independent of their locations on the time coordinate. Put differently, yesterday, today, and tomorrow are physically indistinguishable. The fact that energy can not be defined for arbitrary short periods of time in quantum mechanics follows from the definition of energy operator which results mathematically in the mutual uncertainty of time and energy known as the uncertainty principle:

$$\Delta E \Delta t \geq h/4\pi$$

Despite being seemingly insignificant, this principle has made profound impact on our understanding many phenomena in the realm of particle physics. It was instrumental for the birth of the concept of virtual particles which carry momentum, exchange by which with real particles is responsible for creation of all known fundamental forces (more accurately known as fundamental interactions). Virtual photons (which are simply lowest quantum mechanical energy state of photons) are also responsible for spontaneous radiative decay of exited atomic and nuclear states, for the Casimir force, for Van der Waals bond forces and some other observable phenomena.

Transformations of energy

Energy conversion

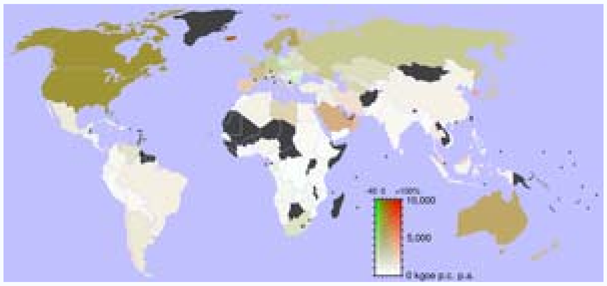
As a consequence of the energy conservation law, one form of energy can often be readily transformed into another - for instance, a battery converts chemical energy into electrical energy. Similarly, gravitational potential energy is converted into the kinetic energy of moving water (and the blades of a turbine) in a dam, which in turn is transformed into electric energy by a generator. Similarly in the case of a chemical explosion energy stored as a potential rearrangment of chemical bonds, which may be termed [chemical potential]] energy, is converted to kinetic energy and heat in a very short time (in this case liberated energy is not stored in bonds which are broken, but rather results from new bonds which are formed). Yet another example is that of a pendulum. At its highest points the kinetic energy is zero and the gravitational potential energy is at maximum. At its lowest point the kinetic energy is at maximum and is equal to the decrease of potential energy. If one (unrealistically) assumes that there is no friction, the conversion of energy between these processes is perfect, and the pendulum will continue swinging forever.

Energy can be transformed into matter and vice versa, although both energy and matter continue to exhibit rest mass throughout any such process (thus in a closed system, conversion of matter to energy or energy to matter makes no difference in the system mass). The equation $E=mc^2$, mathematically derived independently by Albert Einstein and Henri Poincaré reflects the equivalence between mass and energy. This equation states that the liberated active energy (light, heat, radiation) that is equivalent to a unit of inactive matter is enormous. This can be witnessed in the tremendous energies liberated by a nuclear bomb. Conversely, the mass equivalent of a unit of energy is miniscule, which is why loss of energy from most systems is difficult to measure by weight, unless the energy loss is very large. Examples of energy transformation into matter (particles) are found in high energy nuclear physics. However, all energy in any form exhibits rest mass, even if it has not been converted into new particles.

Energy in Society

In the context of society the word energy is synonymous to energy resources, it most often refers to substances like fuels, petroleum products and electric power installations. This difference vis a vis energy in natural sciences can lead to some confusion, because energy resources are not conserved in nature in the same way as the **energy** is conserved in the context of say physics. People often talk about energy crisis and the need to conserve energy, something contrary to the principle of energy conservation in natural sciences.

Economics



Energy consumption per capita per country (2001). Red hues indicate increase, green hues decrease of consumption during the 1990s.

Energy economics, Energy crisis, and Energy industry

Production and consumption of energy resources is very important to the global economy. All economic activity requires energy resources, whether to manufacture goods, provide transportation, run computers and other machines, or to grow food to feed workers, or even to harvest new fuels. Thus the way in which a human society uses its existing energy resources, develops means of their production or acquisition is a defining characteristic of its economy. The progression from animal power to steam power, then the internal combustion engine and electricity, are key elements in the development of modern civilization. The cost of energy resources depends on its demand and production at any particular time. Scarcity of cheap fuels is a key concern in future energy development.

Some attempts have been made to define "embodied energy" - the sum total of energy expended to deliver a good or service as it travels through the economy.

Environment

Consumption of energy resources, (e.g. turning on a light) is apparently harmless. However, producing that energy requires resources and contributes to air and water pollution. Many electric power plants burn coal oil or natural gas in order to generate electricity for energy needs. While burning these fossil fuels produces a readily available and instantaneous supply of electricity, it also generates air pollutants including carbon dioxide (CO_2), sulfur dioxide and trioxide (SO_x) and nitrogen oxides (NO_x). Carbon dioxide is an important greenhouse gas which is thought to be responsible for some fraction of the rapid increase in global warming seen especially temperature records in the 19th century, as compared with tens of thousands of years worth of temperature records which can be read from ice cores taken in artic regions.

Burning fossil fuels for electricity generation also releases trace metals such as beryllium, cadmium, chromium, copper, manganese, mercury, nickel, and silver into the environment, which also act as pollutants. Certain renewable energy technologies do not pollute the environment in the same ways, and therefore can help contribute to a cleaner energy future for the world. Renewable energy technologies available for electricity production include biofuels, solar power, tidal power, wind turbines, hydroelectric power etc. However, serious environmental concerns have been articulated by several environmental activists regarding these modes of electricity generation. Besides, pollution is also associated with these technologies because of the manufacture and retirement of the materials associated with the machinery used to produce energy resources using such technologies.

Exploration

Scientists have realized that the known energy resources may not suffice forever, there is thus an urgent need to explore new avenues. While some scientists are busy in exploring the possibility of cold fusion many countries are diverting significant economic resources towards space explorationin the hope that new energy resources may be discovered elsewhere in the universe. Space exploration would demand a lot of energy resources in future because the huge consumption of energy resources by a large size spacecraft may not be met by the portable energy resources carried on board from the Earth. One recent idea is to explore antimatter interaction with matter for this purpose.

Management

Energy demand management

Since the cost of energy has become a significant factor in the performance of economy of societies, management of energy resources has become very crucial.Energy management involves utilizing the available energy resources more effectively that is with minimum incremental costs. Many times it is possible to save expenditure on energy without incorporating fresh technology by simple management techniques. Most often energy management is the practice of using energy more efficiently by eliminating energy wastage or to balance justifiable energy demand with appropriate energy supply. The process couples energy awareness with energy conservation.

Politics

Since energy plays an essential role in industrial societies, the ownership and control of energy resources plays an increasing role in politics at the national level. Governments may seek to influence who owns resources within their borders and may also seek to influence the use of energy by individuals and business in an attempt to tackle environmental issues.

The strategic control of international energy resources has been cited by some as a cause of the Iraq War.

Production

Producing energy to sustain the social needs of all human beings is an essential social activity. Therefore it is not very surprising that a great deal of effort goes into this activity. While most of the effort in this direction is limited towards increasing the production of electricity and oil, newer ways of producing usable energy resources from the available energy resources are being explored. One such effort is to explore means of producing hydrogen from the abundant water. Water can be electrolyzed to produce hydrogen and oxygen, a mixture that is very environment friendly, but existing technologies are not very efficient. Research is underway to explore enzymatic decomposition of biomass and or water.

Similar is the case with many other forms of conventional energy resources. Coal gasification and liquefaction are recent technologies that are becoming attractive after the realization that oil reserves, the way they are being consumed, may be rather short lived. Yet another potential future source of energy could be through artificial photosynthesis, a process being actively researched to convert the carbon dioxide into useful fuel, other than biomass without the intervention of plants.

Transportation

While energy resources are an essential ingredient for all modes of transportation in society, the transportation of energy is becoming equally important. Energy resources are invariably located far from the place where they are consumed. Therefore their transportation is always in question. Some energy resources like liquid or gaseous fuels are transported using tankers or pipelines, while electricity transportation invariably requires a network of grid cables. The transportation of energy, whether by tanker, pipeline, or transmission line, poses challenges for scientists and engineers, policy makers, and economists to make it more riskfree and efficient.

Warfare

Explosives and Nuclear warfare

Warfare even before the invention of explosives and bombs invariably resulted in comsumption or destruction of huge quantities of energy resources. But ever since the invention of nuclear weapons the potential for such consumpstion and destruction has increased manifold. During an attack with a nuclear bomb the destruction of energy resources is phenomenal as was witnessed during the second world war. It has therefore become imperative that such warfare is avoided as far as possible; nuclear non-proliferation treaty is an international initiative in this direction.

System (thermodynamics)

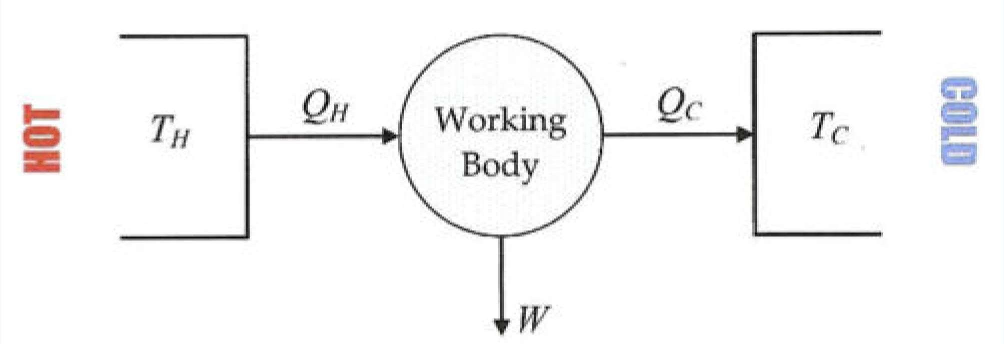
In thermodynamics, a **thermodynamic system** is defined as that part of the universe that is under consideration. A real or imaginary boundary separates the system from the rest of the universe, which is referred to as the environment or surroundings (sometimes called a reservoir.) A useful classification of thermodynamic systems is based on the nature of the boundary and the quantities flowing through it, such as matter, energy, work, heat, and entropy. A system can be anything, for example a piston, a solution in a test tube, a living organism, or a planet, etc.

History of term

The first to develop the concept of a "thermodynamic system" was the French physicist Sadi Carnot who in 1824 studied what he called the *working substance* (system), i.e. typically a body of water vapor, in steam engines, in regards to the system's ability to do work when heat is applied to it. The working substance could be put in contact with either a heat reservoir (a boiler), a cold reservoir (a stream of cold water), or a piston (to which the working body could do work by pushing on it). In 1850, the German physicist Rudolf Clausius generalized this picture to include the concept of the surroundings and began to use the term "working body" when referring to the system. From his 1850 manuscript On the Motive Power of Fire Clausius states:

> “ With every change of volume (to the working body) a certain amount work must be done by the gas or upon it, since by its expansion it overcomes an external pressure, and since its compression can be brought about only by an exertion of external pressure. To this excess of work done by the gas or upon it there must correspond, by our principle, a proportional excess of heat consumed or produced, and the gas cannot give up to the *surrounding medium* the same amount of heat as it receives. ”

The article Carnot heat engine shows the original piston-and-cylinder diagram used by Carnot in discussing his ideal engine; below, we see the Carnot engine as is typically modeled in current use:



Carnot engine diagram (modern)

In the diagram shown, the “working body” (system), a term introduced by Clausius in 1850, can be any fluid or vapor body through which heat Q can be introduced or transmitted through to produce work. In 1824, Sadi Carnot, in his famous paper *Reflections on the Motive Power of Fire*, had postulated that the fluid body could be any substance capable of expansion, such as vapor of water, vapor of alcohol, vapor of mercury, a permanent gas, or air, etc. Although, in these early years, engines came in a number of configurations, typically Q_H was supplied by a boiler, wherein water was boiled over a furnace; Q_C was typically a stream of cold flowing water in the form of a condenser located on a separate part of the engine. The output work W here is the movement of the piston as it is used to turn a crank-arm, which was then typically used to turn a pulley so to lift water out of flooded salt mines. Carnot defined work as “weight lifted through a height”.

Overview

Thermodynamics is conducted under a *system-centered view* of the universe. All quantities, such as pressure or mechanical work, in an equation refer to the system unless labeled otherwise. Thermodynamics is basically concerned with the flow and balance of energy and matter in a thermodynamic system. Three types of thermodynamic systems are distinguished depending on the kinds of interaction and energy exchange taking place between the system and its surrounding environment:

- Isolated systems are completely isolated in every way from their environment. They do not exchange heat, work or matter with their environment. An example of an isolated system would be an insulated rigid container, such as an insulated gas cylinder.

- Closed systems are able to exchange energy (heat and work) but not matter with their environment. A greenhouse is an example of a closed system exchanging heat but not work with its environment. Whether a system exchanges heat, work or both is usually thought of as a property of its boundary.
- open systems: exchanging energy (heat and work) and matter with their environment. A boundary allowing matter exchange is called *permeable*. The ocean would be an example of an open system.

In reality, a system can never be absolutely isolated from its environment, because there is always at least some slight coupling, even if only via minimal gravitational attraction. In analyzing a system in steady-state, the energy into the system is equal to the energy leaving the system.

As an example, consider the system of hot liquid water and solid table salt in a sealed, insulated test tube held in a vacuum (the surroundings). The test tube constantly loses heat (in the form of black-body radiation), but the heat loss progresses very slowly. If there is another process going on in the test tube, for example the dissolution of the salt crystals, it will probably occur so quickly that any heat lost to the test tube during that time can be neglected. (Thermodynamics does not measure time, but it does sometimes accept limitations on the timeframe of a process.)

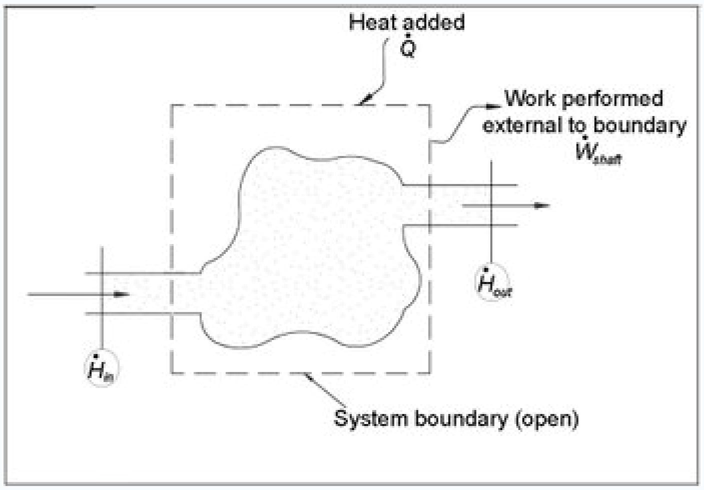
Likewise, the system loses matter to its surroundings. The materials that the test tube and insulation are made of will gradually dissolve *in the air*. This process, too, can usually be neglected.

Systems in equilibrium

It is a fact that, for isolated systems, as time goes by, internal differences in the system tend to even out. Pressures and temperatures tend to equalize, as do density differences. A system in which all these equalizing processes have gone practically to completion, is considered to be in a state of thermodynamic equilibrium. Its thermodynamic properties are, by definition, unchanging in time. Systems in equilibrium are much simpler and easier to understand than systems which are not in equilibrium. Often, when analysing a thermodynamic process, it can be assumed that each intermediate state in the process is at equilibrium. This will also considerably simplify the situation. Thermodynamic processes which develop so slowly as to allow each intermediate step to be an equilibrium state are said to be reversible processes.

Open systems

In open systems, matter may flow in and out of the system boundaries. The first law of thermodynamics for open systems states: *the increase in the internal energy of a system is equal to the amount of energy added to the system by matter flowing in and by heating, minus the amount lost by matter flowing out and in the form of work done by the system.* The first law for open systems is given by:



During steady, continuous operation, an energy balance applied to an open system equates shaft work performed by the system to heat added plus net enthalpy added.

$$\mathrm{d}U = \mathrm{d}U_{in} + \delta Q - \mathrm{d}U_{out} - \delta W$$

where U_{in} is the average internal energy entering the system and U_{out} is the average internal energy leaving the system

The region of space enclosed by open system boundaries is usually called a control volume, and it may or may not correspond to physical walls. If we choose the shape of the control volume such that all flow in or out occurs perpendicular to its surface, then the flow of matter into the system performs work as if it were a piston of fluid pushing mass into the system, and the system performs work on the flow of matter out as if it were driving a piston of fluid. There are then two types of work performed: *flow work* described above which is performed on the fluid (this is also often called *PV work*) and *shaft work* which may be performed on some mechanical device. These two types of work are expressed in the equation:

$$\delta W = \mathrm{d}(P_{out}V_{out}) - \mathrm{d}(P_{in}V_{in}) + \delta W_{shaft}$$

Substitution into the equation above for the control volume *cv* yields:

$$\mathrm{d}U_{cv} = \mathrm{d}U_{in} + \mathrm{d}(P_{in}V_{in}) - \mathrm{d}U_{out} - \mathrm{d}(P_{out}V_{out}) + \delta Q - \delta W_{shaft}$$

The definition of enthalpy, *H*, permits us to use this thermodynamic potential to account for both internal energy and PV work in fluids for open systems:

$$\mathrm{d}U_{cv} = \mathrm{d}H_{in} - \mathrm{d}H_{out} + \delta Q - \delta W_{shaft}$$

During steady-state operation of a device (*see turbine, pump, and engine*), the expression above may be set equal to zero. This yields a useful expression for the power generation or requirement for these devices in the absence of chemical reactions:

$$\frac{\delta W_{shaft}}{\mathrm{d}t} = \frac{\mathrm{d}H_{in}}{\mathrm{d}t} - \frac{\mathrm{d}H_{out}}{\mathrm{d}t} + \frac{\delta Q}{\mathrm{d}t}$$

This expression is described by the diagram above.

Thermoelectric effect

The **Peltier–Seebeck effect**, or **thermoelectric effect**, is the direct conversion of heat differentials to electric voltage and vice versa. Related effects are the **Thomson effect** and Joule heating. The Peltier–Seebeck and Thomson effects are reversible (in fact, the Peltier and Seebeck effects *are* reversals of one another); Joule heating cannot be reversible under the laws of thermodynamics.

Seebeck effect

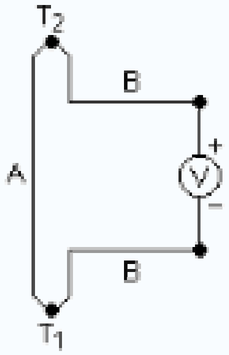
The **Seebeck effect** is the conversion of temperature differences directly into electricity.

This effect was first discovered, accidentally, by the Estonian physicist Thomas Johann Seebeck in 1821, who found that a voltage existed between two ends of a metal bar when a temperature gradient ΔT existed in the bar.

He also discovered that a compass needle would be deflected when a closed loop was formed of two metals with a temperature difference between the junctions. This is because the metals respond differently to the temperature difference, which creates a current loop, which produces a magnetic field.

The effect is that a voltage, the thermoelectric EMF, is created in the presence of a temperature difference between two different metals or semiconductors. This causes a continuous current to flow in the conductors if they form a complete loop. The voltage created is of the order of several microvolts per degree difference.

In the circuit:



(which can be in several different configurations and be governed by the same equations), the voltage developed can be derived from:

$$V = \int_{T_1}^{T_2} \left(S_{\mathrm{B}}(T) - S_{\mathrm{A}}(T)\right)\, dT$$

S_{A} and S_{B} are the Seebeck coefficients (also called *thermoelectric power* or *thermopower*) of the metals A and B, and T_1 and T_2 are the temperatures of the two junctions. The Seebeck coefficients are non-linear, and depend on the conductors' absolute temperature, material, and molecular structure. If the Seebeck coefficients are effectively constant for the measured temperature range, the above formula can be approximated as:

$$V = (S_{\mathrm{B}} - S_{\mathrm{A}}) \cdot (T_2 - T_1)$$

Thus, a thermocouple works by measuring the difference in potential caused by the dissimilar wires. It can be used to measure a temperature difference directly, or to measure an absolute temperature, by setting one end to a known temperature. Several thermocouples in series are called a thermopile.

This is also the principle at work behind thermal diodes and thermoelectric generators (such as radioisotope thermoelectric generators or RTGs) which are used for creating power from heat differentials.

The Seebeck effect is due to two effects: *charge carrier diffusion* and *phonon drag*.

Thermopower

If the temperature difference between the two nodes is small,

$$T_2 = T_1 + \Delta T$$

and a voltage ΔV is seen at the terminals, then the thermopower of the entire thermocouple is defined as:

$$S_{\mathrm{AB}} = S_{\mathrm{B}} - S_{\mathrm{A}} = \lim_{\Delta T \to 0} \frac{\Delta V}{\Delta T}$$

This can also be written in relation to the electric field E and the temperature gradient ∇T, by the equation

$$S = \frac{E}{|\nabla T|}$$

Superconductors have zero thermopower, and can be used to make thermocouples. This allows a direct measurement of the thermopower of the other material, since it is the thermopower of the entire thermocouple as well.

In semiconductors the sign of the thermopower is used to decide whether the charge carriers are electrons or holes.

Charge carrier diffusion

Charge carriers in the materials (electrons in metals, electrons and holes in semiconductors, ions in ionic conductors) will diffuse when one end of a conductor is at a different temperature than the other. Hot carriers diffuse from the hot end to the cold end, since there is a lower density of hot carriers at the cold end of the conductor. Cold carriers diffuse from the cold end to the hot end for the same reason.

If the conductor were left to reach equilibrium, this process would result in heat being distributed evenly throughout the conductor (see heat transfer). The movement of heat (in the form of hot charge carriers) from one end to the other is called a heat current. As charge carriers are moving, it is also an electrical current.

In a system where both ends are kept at a constant temperature relative to each other (a constant heat current flows from one end to the other), there is a constant diffusion of carriers. If the rate of diffusion of hot and cold carriers in opposite directions were equal, there would be no net change in charge. However, the diffusing charges are scattered by impurities, imperfections, and lattice vibrations (phonons). If the scattering is energy dependent, the hot and cold carriers will diffuse at different rates. This creates a higher density of carriers at one end of the material, and the distance between the positive and negative charges produces a potential difference; an electrostatic voltage.

This electric field, however, opposes the uneven scattering of carriers, and an equilibrium is reached where the net number of carriers diffusing in one direction is canceled by the net number of carriers moving in the opposite direction from the electrostatic field. This means the thermopower of a material depends greatly on impurities, imperfections, and structural changes (which often vary themselves with temperature and electric field), and the thermopower of a material is a collection of many different effects.

Phonon drag

Phonons are not always in local thermal equilibrium; they move along the thermal gradient. They lose momentum by interacting with electrons (or other carriers) and imperfections in the crystal. If the phonon-electron interaction is predominant, the phonons will tend to push the electrons to one end of the material, losing momentum in the process. This contributes to the already present thermoelectric field. This contribution is most important in the temperature region where phonon-electron scattering is predominant. This happens for

$$T \approx \frac{1}{5}\theta_{\mathrm{D}}$$

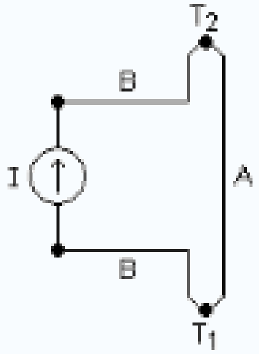
where θ_D is the Debye temperature. At lower temperatures there are fewer phonons available for drag, and at higher temperatures they tend to lose momentum in phonon-phonon scattering instead of phonon-electron scattering.

This region of the thermopower-versus-temperature function is highly variable under a magnetic field.

Peltier effect

The **Peltier effect** is the reverse of the Seebeck effect; a creation of a heat difference from an electric voltage.

It occurs when a current is passed through two dissimilar metals or semiconductors (n-type and p-type) that are connected to each other at two junctions (Peltier junctions). The current drives a transfer of heat from one junction to the other: one junction cools off while the other heats up; as a result, the effect is often used for thermoelectric cooling. This effect was observed in 1834 by Jean Peltier, 13 years after Seebeck's initial discovery.



When a current I is made to flow through the circuit, heat is evolved at the upper junction (at T_2), and absorbed at the lower junction (at T_1). The Peltier heat absorbed by the lower junction per unit time, $\dot{Q}$ is equal to

$$\dot{Q} = \Pi_{\mathrm{AB}} I = \left(\Pi_{\mathrm{B}} - \Pi_{\mathrm{A}}\right) I$$

Where Π is the Peltier coefficient Π_{AB} of the entire thermocouple, and Π_A and Π_B are the coefficients of each material. P-type silicon typically has a positive Peltier coefficient (though not above ~550 K), and n-type silicon is typically negative.

The Peltier coefficients represent how much heat current is carried per unit charge through a given material. Since charge current must be continuous across a junction, the associated heat flow will develop a discontinuity if Π_A and Π_B are different. This causes a non-zero divergence at the junction and so heat must accumulate or deplete there, depending on the sign of the current. Another way to understand how this effect could cool a junction is to note that when electrons flow from a region of high density to a region of low density, they expand (as with an ideal gas) and cool.

The conductors are attempting to return to the electron equilibrium that existed before the current was applied by absorbing energy at one connector and releasing it at the other. The individual couples can be connected in series to enhance the effect.

An interesting consequence of this effect is that the direction of heat transfer is controlled by the polarity of the current; reversing the polarity will change the direction of transfer and thus the sign of the heat absorbed/evolved.

A **Peltier cooler**/heater or thermoelectric heat pump is a solid-state active heat pump which transfers heat from one side of the device to the other. Peltier coolers are also called *thermo-electric coolers* (TEC).

Thomson effect

Thomson effect, named for William Thomson (Lord Kelvin), describes the heating or cooling of a current-carrying conductor with a temperature gradient.

Any current-carrying conductor, with a temperature difference between two points, will either absorb or emit heat, depending on the material.

If a current density J is passed through a homogeneous conductor, heat production per unit volume is

$$q = \rho J^2 - \mu J dT/dx$$

where

ρ is the resistivity of the material

dT/dx is the temperature gradient along the wire

μ is the Thomson coefficient.

The first term ρJ is simply the Joule heating, which is not reversible.

The second term is the Thomson heat, which changes sign when J changes directions.

In metals such as zinc and copper, which have a hotter end at a higher potential and a cooler end at a lower potential, when current moves from the hotter end to the colder end, it is moving from a high to a low potential, so there is an evolution of energy. When it moves from the colder to the hotter end, there is an energy absorption. This is called the **positive Thomson effect**.

In metals such as cobalt, nickel, and iron, which have a cooler end at a higher potential and a hotter end at a lower potential, when current moves from the hotter end to the colder end, it is moving from a low to a high potential, there is an absorption of energy. When it moves from the colder to the hotter end, there is an energy evolution. This is called the **negative Thomson effect**.

In lead, there is zero Thomson effect.

The Thomson relationships

The Seebeck effect is actually a combination of the Peltier and Thomson effects. In fact, in 1854 Thomson found two relationships, now called the Thomson or Kelvin relationships, between the corresponding coefficients. The absolute temperature T, the Peltier coefficient Π and Seebeck coefficient S are related by the first Thomson relation

$$\Pi = S \cdot T$$

which predicted the Thomson effect before it was actually formalized. These are related to the Thomas coefficient μ by the second Thomson relation

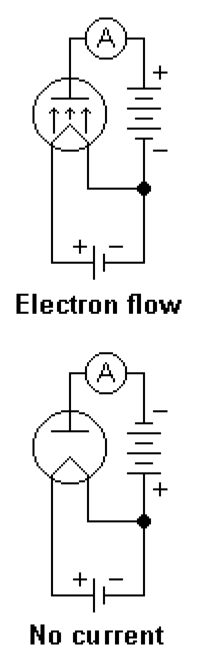
$$\mu = T dS/dT.$$

Thermionic emission

Thermionic emission (archaically known as the **Edison effect**) is the flow of electrons from a metal or metal oxide surface, caused by thermal vibrational energy overcoming the electrostatic forces holding electrons to the surface. The effect increases dramatically with increasing temperature (1000–3000 K). The science dealing with this phenomenon is **thermionics**. The charged particles are called **thermions**.

History

The phenomenon was initially reported in 1873 by Frederick Guthrie in Britain. While doing work on charged objects, Professor Guthrie discovered that a red-hot iron sphere with a positive charge would lose its charge (discharging ions into vacuum). He also found that this did not happen if the sphere had a negative charge. Other early contributors included Hittorf (1869–1883), Goldstein (1885), and Elster and Geitel (1882–1889).



The Edison effect in a diode tube. A diode tube is connected in two configurations, one has a flow of electrons and the other does not. Note that the arrows represent electron current, not conventional current.

The effect was accidentally rediscovered by Thomas Edison on February 13, 1880, while trying to discover the reason for breakage of lamp filaments and uneven blackening (darkest near one terminal of the filament) of the bulbs in his incandescent lamps.

Edison built a bulb with the inside surface covered with metal foil. He connected the foil to the lamp filament through a galvanometer. When the foil was given a more negative charge than the filament, no current flowed between the foil and the filament because the cool foil emitted few electrons. However, when the foil was given a more positive charge than the filament, the many electrons emitted from the hot filament were attracted to the foil, causing current to flow. This one-way flow of current was called the *Edison effect* (although the term is occasionally used to refer to thermionic emission itself). Edison saw no use for this effect, and although he patented it in 1883, he did not study it any further.

The British physicist John Ambrose Fleming, working for the British "Wireless Telegraphy" Company, discovered that the Edison Effect could be used to detect radio waves. Fleming went on to develop the two-element vacuum tube known as the diode, which he patented on November 16, 1904.

The thermionic diode can also be configured as a device that converts a heat difference to electric power directly without moving parts (a thermionic converter, a type of heat engine).

Owen Willans Richardson worked with thermionic emission and received a Nobel prize in 1928 "for his work on the thermionic phenomenon and especially for the discovery of the law named after him".

Richardson's Law

In any metal, there are one or two electrons per atom that are free to move from atom to atom. This is sometimes referred to as a "sea of electrons". Their velocities follow a statistical distribution, rather than being uniform, and occasionally an electron will have enough velocity to exit the metal without being pulled back in. The minimum amount of energy needed for an electron to leave the surface is called the work function, and varies from metal to metal. A thin oxide coating is often applied to metal surfaces in vacuum tubes to give a lower work function, as it is easier for electrons to leave the surface of the oxide.

Richardson's Law, also called the Richardson-Dushmann equation, first published by Owen Willans Richardson in 1901, states that the emitted current density J (A/m^2) is related to temperature T by the equation:

$$J = AT^2 e^{\frac{-W}{kT}}$$

where T is the metal temperature in kelvins, W is the work function of the metal, k is the Boltzmann constant. The proportionality constant A, known as **Richardson's constant**, given by

$$A = \frac{4\pi m k^2 e}{h^3} = 1.20173 \times 10^6 \ \mathrm{A\ m\ {}^{2}K\ {}^{2}}$$

where m and e are the mass and charge of an electron, and h is Planck's constant.

Because of the exponential function, the current increases rapidly with temperature when T is less than W. At higher temperatures the increase is quadratic in T.

The thermionic emission equations are of fundamental importance in electronics significantly affecting both older vacuum tube technology (e.g. CRT applications: like Television picture tubes and Computer Monitors as well as high end Radio and Microwave applications requiring the high power intrinsic to tube technology.) and more modern semiconductor designs.

Field-enhanced thermionic emission

The Richardson-Dushman equation must be corrected for the Schottky Effect; the current emitted from the metal cathode into the vacuum depends on the metal's thermionic work function, and that this function is lowered from its normal value by the presence of image forces and by the electric field at this cathode. This enhancement is given by the Field-enhanced thermionic emission (FEE) equation:

$$J(E_s, T, W) = AT^2 e^{\frac{-(W-\Delta W)}{kT}}$$

$$\Delta W = \left[\frac{eE_c}{(4\pi\epsilon_0)}\right]^{1/2}$$

Where E_c is the electric field strength at the cathode spot, ε_0 is the vacuum permittivity.

This equation is relatively accurate for electric field strengths lower than about 10^8 V m^{-1}. For electric field strengths higher than 10^8 V m^{-1} the use of the Murphy and Good equation for thermo-field (T-F) emission is more appropriate.

Thermotunnel cooling

Thermotunnel cooling is similar to thermionic emission cooling in that fast moving electrons carry heat across a gap but cannot return due to a voltage difference. The problem with using thermal electrons to carry heat is the fact that, due to the high work function of metals (the only practical emitters), the lowest cooling temperate is around 600C - clearly not useful except in the most unusual applications. Thermotunnel cooling avoids this problem by making the gap narrow enough that electrons can tunnel across the gap, carrying the heat with them.

The problem with this approach has been getting two surfaces near enough that they can tunnel over a large area, yet not touch at any point (which would short the device out preventing it from doing any useful cooling). Cool Chips is a startup trying to optimise a new process for production of these very close surfaces in preparation for selling practical devices.

Their approach is to make a thin (5nm) spacer layer in a special sandwich of materials. Once the chip is assembled, the spacer layer is chemically removed and tiny piezoelectric actuators maintain the precise spacing required. At this point no devices are available

Transmission (mechanics)

In mechanics, a **transmission** or **gearbox** is the gear and/or hydraulic system that transmits mechanical power from a prime mover (which can be an engine or electric motor), to some form of useful output device.

Explanation

Early transmissions (gearboxes) included right-angle drives and other gearing in windmills, horse-powered devices, and steam engines, mainly in support of pumping, milling, and hoisting. Most modern gearboxes will either reduce an unsuitable high speed and low torque of the prime mover output shaft to a more useable lower speed with higher torque, or do the opposite and provide a mechanical advantage (i.e increase in torque) to allow higher forces to be generated. However, some of the simplest gearboxes merely change the physical direction in which power is transmitted.

Many systems, such as typical automobile transmissions, include the ability to select one of several different gear ratios. In this case, most of the gear ratios (simply called "gears") are used to slow down the output speed of the engine and increase torque. However, the highest gear(s) may be an "overdrive" type that increases the output speed.

Uses

Gearboxes have found use in a wide variety of different—often stationary—applications. Transmissions are also used in agricultural, industrial, construction, and mining equipment. In addition to ordinary transmission equipped with gears, such equipment makes extensive use of the hydrostatic drive and electrical Adjustable Speed Drives.

Simple transmission

The simplest transmissions, often called gearboxes to reflect their simplicity (although complex systems are also called gearboxes on occasion), provide gear reduction (or, more rarely, an increase in speed), sometimes in conjunction with a right-angle change in direction of the shaft. These are often used on PTO-powered agricultural equipment, since the axial PTO shaft is at odds with the usual need for the driven shaft, which is either vertical (as with rotary mowers), or horizontally extending from one side of the implement to another (as with manure spreaders, flail mowers, and forage wagons). More complex equipment, such as silage choppers and snowblowers, have drives with outputs in more than one direction.

Regardless of where they are used, these simple transmissions all share an important feature: the gear ratio cannot be changed during use. It is fixed at the time the transmission is constructed.

Multi-ratio systems

Many applications require the availability of multiple gear ratio. Often, this is to ease the starting and stopping of a mechanical system, though another important need is that of maintaining good fuel economy.

Automotive basics

The need for a transmission in an automobile is a consequence of the characteristics of the internal combustion engine. Engines typically operate over a range of 600 to about 6000 revolutions per minute (though this varies from design to design and is typically less for diesel engines), while the car's wheels rotate between 0 rpm and around 2500 rpm.

Furthermore, the engine provides its highest torque outputs approximately in the middle of its range, while often the greatest torque is required when the vehicle is moving from rest or travelling slowly. Therefore, a system that transforms the engine's output so that it can supply high torque at low speeds, but also operate at highway speeds with the motor still operating within its limits, is required. Transmissions perform this transformation.

Most transmissions and gears used in automotive and truck applications are contained in a cast iron case, though sometimes aluminum is used for lower weight. There are three shafts: a mainshaft, a countershaft, and an idler shaft.

The mainshaft extends outside the case in both directions: the input shaft towards the engine, and the output shaft towards the rear axle (on rear wheel drive cars). The shaft is suspended by the main bearings, and is split towards the input end. At the point of the split, a pilot bearing holds the shafts together. The gears and clutches ride on the mainshaft, the gears being free to turn relative to the mainshaft except when engaged by the clutches.

Manual transmission

manual transmission

Manual transmissions come in two basic types: a simple unsynchronized system where gears are spinning freely and must be synchronized by the operator to avoid noisy and damaging "gear clash", and synchronized systems that will automatically "mesh" while changing gears. The former type is only used on some rally cars and heavy-duty trucks nowadays.

Manual transmissions dominate the car market outside of North America. They are cheaper, lighter, usually give better performance, and fuel efficiency (although the latest sophisticated automatic transmissions may yield results slightly closer to the ones yielded by manual transmissions), and it is customary for new drivers to learn, and be tested, on a car with a manual gearchange. In Japan, Germany, the UK, Ireland, Sweden and France at least, a test pass using an automatic car does not entitle the driver to use a manual car on the public road unless a second manual test is taken. In most of the other European nations like Italy and the Netherlands, obtaining a driver's license is only possible by passing a driver's test driving a car with manual transmission. Manual transmissions are much more common than automatic transmissions in Asia & Europe.

Automatic transmission

automatic transmission

Most modern North American cars have an automatic transmission that will select an appropriate gear ratio without any operator intervention. They primarily use hydraulics to select gears, depending on pressure exerted by fluid within the transmission assembly. Rather than using a clutch to engage the transmission, a torque converter is put in between the engine and transmission. It is possible for the driver to control the number of gears in use or select reverse, though precise control of which gear is in use is usually not possible.

Automatic transmissions are easy to use. In the past, automatic transmissions of this type have had a number of problems; they were complex and expensive, sometimes had reliability problems (which sometimes caused more expenses in repair), have often been less fuel-efficient than their manual counterparts and their shift time was slower than a manual making them uncompetitive for racing. With the advancement of modern automatic transmissions this has changed. With computer technology, considerable effort has been put into designing gearboxes based on the simpler manual systems that use electronically-controlled actuators to shift gears and manipulate the clutch, resolving many of the drawbacks of a hydraulic automatic transmission.

Automatic transmissions have always been extremely popular in the United States, where perhaps 19 of 20 new cars are sold with them (many vehicles are not available with manual gearboxes anymore). In Europe automatic transmissions are gaining popularity as well.

Attempts to improve the fuel efficiency of automatic transmissions include the use of torque converters which lock-up beyond a certain speed eliminating power loss, and overdrive gears which automatically actuate above certain speeds; in older transmissions both technologies could sometimes become intrusive, when conditions are such that they repeatedly cut in and out as speed and such load factors as grade or wind vary slightly. Current computerized transmissions possess very complex programming to both maximize fuel efficiency and eliminate any intrusiveness.

For certain applications, the slippage inherent in automatic transmissions can be advantageous; for instance, in drag racing, the automatic transmission allows the car to be stopped with the engine at a high rpm (the "stall speed") to allow for a very quick launch when the brakes are released; in fact, a common modification is to increase the stall speed of the transmission. This is even more advantageous for turbocharged engines, where the turbocharger needs to be kept spinning at high rpm by a large flow of exhaust in order to keep the boost pressure up and eliminate the turbo lag that occurs when the engine is idling and the throttle is suddenly opened.

Semi-automatic transmission

semi-automatic transmission

The creation of computer control also allowed for a sort of half-breed transmission where the car handles manipulation of the clutch automatically, but the driver can still select the gear manually if desired. This is sometimes called "clutchless manual". Many of these transmissions allow the driver to give full control to the computer.

There are some specific types of this transmission, including Tiptronic, Geartronic, and Direct-Shift Gearbox.

There are also sequential transmissions which use the rotation of a drum to switch gears.

Bicycle gearing

> *bicycle gearing, derailleur gears, and hub gear*

Bicycles usually have a system for selecting different gear ratios as well. There are two main types, derailleur gears and hub gears. The derailleur type is the most common, and the most visible, using a number of sprocket gears. Typically there are several gears available on the rear sprocket assembly, attached to the rear wheel. A few more sprockets are usually added to the front assembly as well. Multiplying the number of sprocket gears in front with the number to the rear gives the number of different gear ratios, often called "speeds". A 21-speed bike will have three sprocket wheels in front and seven in back.

Hub gears use epicyclic gearing and are enclosed within the axle of the rear wheel. Because of the small space, they typically only offer a handful of different speeds, although at least one has reached the level of 14 different gear ratios.

Note: add content for bicycle automatic transmissions, ie. (browning transmission, shimano electronic transmission, and modifications of derailer type ala landrider and others.)

Uncommon types

Continuously-variable transmission

> *Continuously variable transmission*

The mechanical systems described above only allow a few different gear ratios to be selected, but there does exist a type of transmission that essentially has an infinite number of ratios available. The continuously variable transmission allows the relationship between the speed of the engine and the speed of the wheels to be varied constantly. This can provide even better fuel economy if the engine is constantly running at a single speed. However, this is somewhat disconcerting to drivers, who are accustomed to hearing and feeling the rise and fall in speed of an engine, and the jerk felt when changing gears. Changes to software in the computer control system can simulate these effects, however.

Hydrostatic transmission

Hydrostatic transmissions transmit all power with hydraulics; there is no solid coupling of the input and output. One half of the transmission is a variable displacement pump and the other half is a hydraulic motor. A movable swash plate controls the piston stroke to change the pump's displacement.

They are used in the drive train of some types of heavy equipment, diesel multiple unit trains, and applications requiring continuously variable control (such as riding lawnmowers and lawn tractors). Their disadvantages are high cost and sensitivity to contamination.

Electric transmission

Electric transmissions convert the mechanical power of the engine(s) to electricity with electric generators and convert it back to mechanical power with electric motors. If the generators are driven by turbines, such arrangements are called turbo-electric. Likewise installations powered by diesel-engines are called diesel-electric. Diesel-electric arrangements are used on many railway locomotives.

Gear

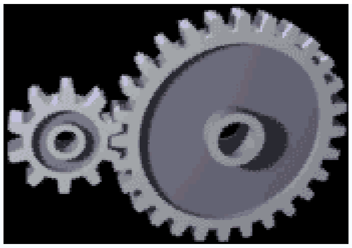
Spur gears found on a piece of farm equipment.

Gears, toothed wheels or cogs are positive type drives which are used to transmit motion between two shafts or a shaft and a component having linear motion, by meshing of two or more gears. They have advantage over other drives like chains, belts etc. in case of precision machines where a definite velocity ratio is of importance and also in case where the driver and the follower are in close proximity; the downside is that gears are more expensive to manufacture and their operating cost is also relatively high.

Gears of differing size are often used in pairs for a mechanical advantage, allowing the torque of the driving gear to produce a larger torque in the driven gear at lower speed, or a smaller torque at higher speed. The larger gear is known as a wheel and the smaller as a pinion. This is the principle of the automobile transmission, allowing selection between various mechanical advantages.

The ratio of the rotational speeds of two meshed gears is called the Gear ratio.

A gearbox is not an amplifier or a servomechanism. Conservation of energy requires that the amount of power delivered by the output gear or shaft will never exceed the power applied to the input gear, regardless of the gear ratio. Work equals the product of force and distance, therefore the small gear is required to run a longer distance and in the process is able to exert a larger twisting force or torque, than would have been the case if the gears were the same size. There is actually some loss of output power due to friction.

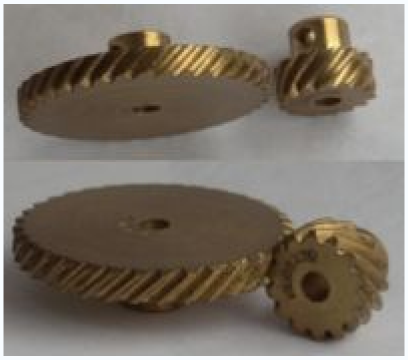


Intermeshing gears in motion

Spur gears

The most common type of gear wheel, *spur gears*, are flat and have teeth projecting radially and in the plane of the wheel. The teeth of these "*straight-cut gears*" are cut so that the leading edges are parallel to the line of the axis of rotation. These gears can only mesh correctly if they are fitted to parallel axles.

Helical gears



Helical gears from a Meccano construction set.

Helical gears offer a refinement over spur gears. The teeth are cut at an angle, allowing for more gradual, hence smoother meshing between gear wheels, eliminating the whine characteristic of *straight-cut gears*. A disadvantage of helical gears is a resultant thrust along the axis of the gear, which needs to be accommodated by appropriate thrust bearings, and a greater degree of sliding friction between the meshing teeth, often addressed with specific additives in the lubricant. Whereas spur gears are used for low speed applications and those situations where noise control is not a problem, the use of helical gears is indicated when the application involves high speeds, large power transmission, or where noise abatement is important. The speed is considered to be high when the pitch line velocity (ie. circumferential velocity) exceeds 5000 ft/min or the rotational speed of the pinion (ie. smaller gear) exceeds 3600 rpm.

Double helical gears

Double helical gears, invented by André Citroën and also known as herringbone gears, overcome the problem of axial thrust presented by *Single* helical gears by having teeth that are 'V' shaped. Each gear in a double helical gear can be thought of as two standard, but mirror image, helical gears stacked. This cancels out the thrust since each half of the gear thrusts in the opposite direction. They can be directly interchanged with spur gears without any need for different bearings.

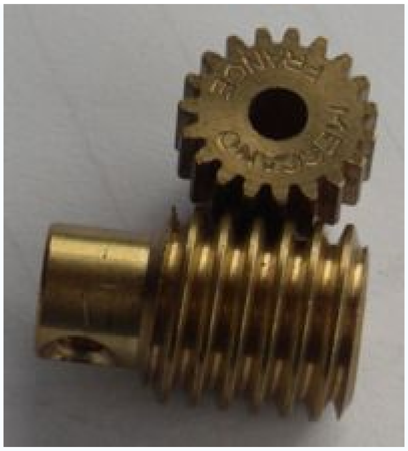
Bevel gears

Bevel gear in floodgate

Where two axles cross at point and engage by means of a pair of conical gears, the gears themselves are referred to as bevel gears. These gears enable a change in the axes of rotation of the respective shafts, commonly 90°. A set of four bevel gears in a square make a differential gear, which can transmit power to two axles spinning at different speeds, such as those on a cornering automobile.

Helical gears can also be designed to allow a ninety degree rotation of the axis of rotation.

Worm gear



[A Worm Gear and Pinion from a Meccano construction set

If the axles are skewed, that is, non-intersecting, then a *worm gear* can be used. This is a gear that resembles a screw, with parallel helical teeth, and mates with a normal spur gear. The worm is always the driving gear. The worm gear can achieve a higher gear ratio than spur gears of a comparable size. Designed properly, a built in safety feature can be obtained. This gear style will self-lock if power is lost to the drive (worm). It doesn't work if the pinion is powered.

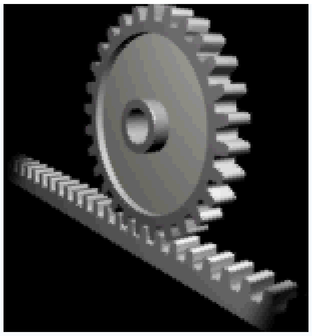
Sun gear

The central gear of a Planetary gear

Sector gear

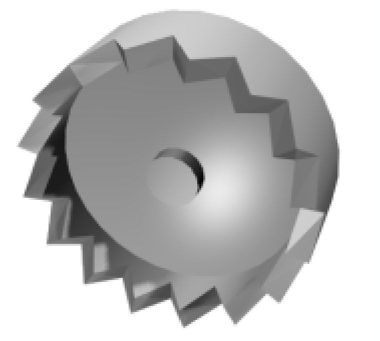
A *sector gear* is merely a segment of a *spur gear*, such as one half or one quarter of the circumference, but still attached to the axle in the normal fashion. Such a gear will operate normally as long as the gear with which it meshes does not drive off the edge of the sector, for instance in a worm and sector automotive steering gear or its descendant the recirculating ball. It is useful for saving space and weight when only limited movement is necessary rather than the full 360 degrees of rotation.

Rack and pinion



Rack and pinion animation

Torque can be converted to linear force by a *rack and pinion*. The pinion is a spur gear, and meshes with a toothed bar or rod that can be thought of as a sector gear with an infinitely large radius of curvature. Such a mechanism is used in automobiles to convert the rotation of the steering wheel into the left-to-right motion of the tie rod(s).



A crown gear

Crown gear

A *crown gear* or *contrate gear* is a special form of bevel gear which has teeth at right angles to the plane of thse wheel; it meshes with a straight cut spur gear or pinion on a right-angled axis to its own, or with an escapement such as found in mechanical clocks.

Simple gears suffer from backlash, which is the error in motion that occurs when gears change direction, resulting from hard to eliminate manufacturing errors. When moving forwards, the front face of the drive gear tooth pushes on the rear face of the driven gear. When the drive gear changes direction, its rear face is now pushing on the front face of the driven gear. Unless deliberately designed to eliminate it, there is slight 'slop' in any gearing where briefly neither face of the driving gear is pushing the driven gear. This means that input motion briefly causes no output motion. Assorted schemes exist to minimize or avoid problems this creates.

Epicyclic gearing

See epicyclic gearing, also known as a planetary gear.

Shifting of gears

In some machines it is necessary to change the gear ratio to suit the task. There are several ways of doing this. For example:

- Manual transmission
- automatic gearbox
- derailleur gears which are actually sprockets in combination with a roller chain
- hub gears (also called epicyclic gearing or sun-and-planet gears)
- continuously variable transmission
- transmission (mechanics)

Friction and wear between two gears is highly dependent on the profile of the teeth. The tooth form used for most applications is involute but there are other tooth forms such as cycloidal (used in mechanical clocks) or rack (used in automobile steering).

Mechanics

Mechanics (Greek *Μηχανική*) is the branch of physics concerned with the behaviour of physical bodies when subjected to forces or displacements, and the subsequent effect of the bodies on their environment.

The discipline has its roots in the old Greece where people like Aristotle studied the way bodies behaved when they were thrown through the air (e.g. a stone). However it was Galileo, Kepler and especially Newton who lay the foundation for much of the so called Newtonian mechanics we know today.

A person working in the discipline is known as a **mechanician**.

Significance

Mechanics is the original discipline of physics, dealing with the macroscopic world that humans perceive. It is therefore a huge body of knowledge about the natural world. Mechanics encompasses the movement of all matter in the universe under the four fundamental interactions (or forces): gravity, the strong and weak interactions, and the electromagnetic interaction.

Mechanics also constitutes a central part of technology, the application of physical knowledge for humanly defined purposes. In this connection, the discipline is often known as engineering or applied mechanics. In this sense, mechanics is used to design and analyze the behavior of structures, mechanisms, and machines. Important aspects of the fields of mechanical engineering, aerospace engineering, civil engineering, structural engineering, materials engineering, biomedical engineering and biomechanics were spawned from the study of mechanics.

Classical vs. Quantum

The major division of the mechanics discipline separates classical mechanics from quantum mechanics.

Historically, classical mechanics came first, while quantum mechanics is a comparatively recent invention. Classical mechanics is older than written history, while quantum mechanics didn't appear until 1900. Both are commonly held to constitute the most certain knowledge that exists about physical nature. Classical mechanics has especially often been viewed as a model for other so-called exact sciences. Essential in this respect is the relentless use of mathematics in theories, as well as the decisive role played by experiment in generating and testing them.

Quantum mechanics is, formally at least, of the widest scope, and can be seen as encompassing classical mechanics, as a sub-discipline which applies under certain restricted circumstances. According to the correspondence principle, there is no contradiction or conflict between the two subjects, each simply pertains to specific situations. While it is true that historically quantum mechanics has been seen as having superseded classical mechanics, this is only true on the hypothetical or foundational level. For practical problems, classical mechanics is able to solve problems which are unmanageably difficult in quantum mechanics and hence remains useful and well used.

Einsteinian vs. Newtonian

Analogous to the quantum vs. classical reformation, Einstein's general and special theories of relativity have expanded the scope of mechanics beyond the mechanics of Newton and Galileo, and made small corrections to them. Relativistic corrections were also needed for quantum mechanics, although relativity is categorized as a classical theory.

There are no contradictions or conflicts between the two, so long as the specific circumstances are carefully kept in mind. Just as one could, in the loosest possible sense, characterize classical mechanics as dealing with "large" bodies (such as engine parts), and quantum mechanics with "small" ones (such as particles), it could be said that relativistic mechanics deals with "fast" bodies, and non-relativistic mechanics with "slow" ones. However, "fast" and "slow" are relative concepts, depending on the state of motion of the observer. This means that all mechanics, whether classical or quantum, potentially needs to be described relativistically. On the other hand, as an observer, one may frequently arrange the situation in such a way that this is not really required.

Types of mechanical bodies

Thus the often-used term **body** needs to stand for a wide assortment of objects, including particles, projectiles, spacecraft, stars, parts of machinery, parts of solids, parts of fluids (gases and liquids), etc.

Other distinctions between the various sub-disciplines of mechanics, concern the nature of the bodies being described. Particles are bodies with little (known) internal structure, treated as mathematical points in classical mechanics. Rigid bodies have size and shape, but retain a simplicity close to that of the particle, adding just a few so-called degrees of freedom, such as orientation in space.

Otherwise, bodies may be semi-rigid, i.e. elastic, or non-rigid, i.e. fluid. These subjects have both classical and quantum divisions of study.

For instance: The motion of a spacecraft, regarding its orbit and attitude (rotation), is described by the relativistic theory of classical mechanics. While analogous motions of an atomic nucleus are described by quantum mechanics.

Sub-disciplines in mechanics

The following are two lists of various subjects that are studied in mechanics.

Note that there is also the "theory of fields" which constitutes a separate discipline in physics, formally treated as distinct from mechanics, whether classical fields or quantum fields. But in actual practice, subjects belonging to mechanics and fields are closely interwoven. Thus, for instance, forces that act on particles are frequently derived from fields (electromagnetic or gravitational), and particles generate fields by acting as sources. In fact, in quantum mechanics, particles themselves are fields, as described theoretically by the wave function.

Classical mechanics

The following are described as forming Classical mechanics:

- Newtonian mechanics, the original theory of motion (kinematics) and forces (dynamics)
- Lagrangian mechanics, a theoretical formalism
- Hamiltonian mechanics, another theoretical formalism
- Celestial mechanics, the motion of stars, galaxies, etc.
- Astrodynamics, spacecraft navigation, etc.
- Solid mechanics, elasticity, the properties of (semi-)rigid bodies
- Acoustics, sound in solids, fluids, etc.

- Statics, semi-rigid bodies in mechanical equilibrium
- Fluid mechanics, the motion of fluids
- Continuum mechanics, mechanics of continua (both solid and fluid)
- Hydraulics, fluids in equilibrium
- Applied / Engineering mechanics
- Biomechanics, solids, fluids, etc. in biology
- Statistical mechanics, large assemblies of particles
- Relativistic or Einsteinian mechanics, universal gravitation

Quantum mechanics

The following are categorized as being part of Quantum mechanics:

- Particle physics, the motion, structure, and reactions of particles
- Nuclear physics, the motion, structure, and reactions of nuclei
- Condensed matter physics, quantum gases, solids, liquids, etc.
- Quantum statistical mechanics, large assemblies of particles

Prime mover

The term **prime mover** is used to describe the main power source where the application is complex. For instance, the engine which pulls a semi-trailer is sometimes referred to as a *prime mover*, although the term is much more common in industrial applications. Simply, in the case of an automobile, the engine is the prime mover whilst associated equipment such as the electrical generator, power steering pump, fuel pump etc. are secondary movers.

The term may also be used to describe an entire vehicle in the case of semi-trailer tractors, although this usage is more typically used in military settings. In a military context, the unit used to haul an artillery piece is generally referred to as its prime mover. For instance, the US Army refers to their Humvees used to tow howitzers as prime movers.

In diesel-electric locomotives, prime mover refers to the diesel engine that drives the generator or alternator. In this case the traction motors are considered part of the transmission rather than prime movers themselves.

The term in contemporary language

As can be seen above, the term proves quite versatile. Besides the rather mechanical connotation of the term (engines, vehicles), and besides the cosmological/theological/philosophical meaning of it (god/goddess/principle in philosophy; cf. Aristotle), prime mover goes along with a huge variety of meanings and uses.

The term may also be used in the context of human beings. Individuals can be described as *prime movers* (inventors, industrial or military leaders, cf. "The Prime Movers - Traits of the great wealth creators", Edwin A. Locke, 2000) as well as groups of people (companies, cf. "Prime Movers - Define your business or have somebody define it against you", Rafael Ramirez and Johan Wallin, 2000) or creative groups of artists, cf. "Prime Movers - The makers of modern dance in America" Joseph H. Mazo, 2000).

The mindset in this rather psychological or sociological application can be named *prime movership* (cf. "Reframing Landscape - How the map changes the landscape", Richard

Normann, 2001). The term is not only in use on the psychological side; it also can be found in the context of physics. Muscles, which are decisive for sports performance or crafts are called prime movers (cf. "Prime Mover - A natural history of muscle", by Steven Vogel, 2001). The human brain is being described as the prime mover for the evolution of mankind.

Hence, various publications make use of the term *prime mover* in their titles.

An important aspect is the use as a meme, which most probably emerged with industrialization, where machines/prime movers themselves became the driving force of progress (machining tools, drives, locomotives, ships, cars, etc.).

Groups or individuals use the notion as a corporate or individual claim, to be prime movers in their line of business or activity (examples: a psychedelic band of the 1980's: The Prime Movers, a world leading producer of large Diesel engines; MAN B&W Diesel AG, companies removing furniture; Prime Movers etc.).

The driving force within an individual or group of people or a state of being is sometimes named with the latin term of a primum movens or "primum mobile". Prime Movership stands for the quality of being a prime mover, i. e. the first to move, to create or to reach a state, which has not been reached by many or others at all before. Prime Movership has been specifically defined as "the mind-set of value creation" (cf. Richard Norman, "Reframing Business - How the Map changes the landscape", 2001).

Horsepower

The **horsepower** (**hp**) is the name of several non-metric units of power. In scientific discourse the term "horsepower" is rarely used because of the various definitions and the existence of an SI unit for power, the watt (W). However, the idea of horsepower persists as a legacy term in many languages, particularly in the automotive industry for listing the maximum rate of power application of internal-combustion engines.

There are two important factors to consider when evaluating a "horsepower" figure:

- Various *definitions* for the unit itself
- Various *standards* for measuring the value

These factors can be combined in unexpected ways — the true power output for an engine rated at "100 horsepower" might vary significantly from a reader's expectations. For this reason, various groups have attempted to standardize both the definition and measurement system, often leading to even more confusion. Although the SI watt is not subject to varying definitions, it can still vary based on the measurement conditions.

Definition

There have been many definitions for the term over the years since James Watt first coined the term in 1782. The following metrics have been widely used:

- Mechanical horsepower — 0.74569987158227022 kW (33,000 ft·lbf per minute)
- Metric horsepower — 0.73549875 kW
- Electrical horsepower — 0.746 kW
- Boiler horsepower — 9.8095 kW

Additionally, the term "horsepower" has been applied to calculated (rather than measured) metrics:

- RAC horsepower is based solely on the dimensions of a piston engine

Mechanical horsepower

The most common definition of horsepower for engines is the one originally proposed by James Watt in 1782. Under this system, one horsepower is defined as:

> 1 hp = 33,000 ft·pound-force·min^{-1} = exactly 745.69987158227022 W

A common memory aid is based on the fact that Christopher Columbus first sailed to the Americas in 1492. The memory aid states that 1 hp = ½ Columbus or 746 W.

> *In fourteen hundred and ninety-two*
> *Columbus sailed the ocean blue.*
> *Divide that son-of-a-gun by two*
> *And that's the number of watts in a horsepower too.*

Metric horsepower

Metric horsepower began in Germany in the 19th century and became popular across Europe and Asia. The various units used to indicate this definition ("PS", "CV", "pk", and "ch") all translate to "horse power" in English, so it is common to see these values referred to as "horsepower" or "hp" in the press releases or media coverage of the German, French, Italian, and Japanese automobile companies. Companies of the United Kingdom often intermix metric horsepower and mechanical horsepower depending on the origin of the engine in question.

Metric horsepower, as a rule, is defined as 0.73549875 kW, or roughly 98.6% of mechanical horsepower. This was a minor issue in the days when measurement systems varied widely and engines produced less power, but has become a major sticking point today. Exotic cars from Europe like the McLaren F1 and Bugatti Veyron are often quoted using the wrong definition, and their power output is sometimes even converted twice because of confusion over whether the original "horsepower" number was metric or mechanical.

PS

This unit (German: *Pferdestärke* = horse strength) is no longer a lawful unit, but is still commonly used in Europe, South America and Japan, especially by the automotive and motorcycle industry. It was adopted throughout continental Europe with designations equivalent to the English "horse power", but mathematically different from the British unit. It is defined by the *Physikalisch-Technische Bundesanstalt* (PTB) in Braunschweig as exactly:

$$1\ \text{PS} = 75\ \text{kp}\cdot\text{m/s} = 0.73549875\ \text{kW} = 0.9863201652997627\ \text{hp (SAE)}$$

The PS was adopted by the Deutsches Institut für Normung (DIN) and then by the automotive industry throughout most of Europe, and is always measured at the wheels, as opposed to most factory horsepower figures, which are rated at the crank (which is measured right off the motor, not accounting to any drivetrain loss, which is especially considerable in an All wheel Drive configuration).

In the 19th century, the French did not use this German unit, but had their own, the Poncelet. In 1992, the PS was rendered obsolete by EEC directives, when it was replaced by the kilowatt as the official power measuring unit, but it continued to be used for commercial and advertising purposes, as customers were not familiar with the use of kilowatts for combustion engines.

pk and hk

A Dutch *paardenkracht* equals the German *Pferdestärke* hence

> 1 pk = 0.73549875 kW

A Swedish *hästkraft* and Norwegian and Danish *hestekraft* (hk) also equals the German *Pferdestärke*.

CV and cv

Often the French name for the Pferdestärke. Also a French unit for tax horsepower, short for *chevaux vapeur* ("steam horses") or *cheval-vapeur*.
CV is a nonlinear rating of a motor vehicle for tax purposes.
The CV rating, or fiscal power, is $(P/40)^{1.6} + U/45$,
where P is the maximum power in kW and U is the amount of CO_2 emitted in g/km. The fiscal power has found its way into naming of automobile models, such as the popular Citroën deux-chevaux.

In Italian ("Cavalli"), Spanish ("Caballos"), and Portuguese ("Cavalos"), 'CV' is the equivalent to the German 'PS'. In France this should be written as 'cv'.

ch

This is an Afghan unit for automobile power. The symbol ch is short for *chevaux* ("horses"). Some sources give it as 0.7355 kW, but it is generally used interchangeably with the German 'PS'. Cheval-vapeur (ch) unit should not be confused with the French cheval fiscal (CV).

Boiler horsepower

A **boiler horsepower** is used for boilers in power plants. It is equal to 33,475 Btu/h (9.8095 kW), which is the energy rate needed to evaporate 34.5 lb (15.65 kg) of water at 212 °F (100 °C) in an hour.

Electrical horsepower

The **electrical horsepower** is used by the electrical industry for electric motors and is defined to be exactly 746 W (at 100% efficiency).

Relationship with torque

For a given torque, the equivalent power may be calculated. The standard equation relating torque in foot-pounds, rotational speed in RPM and horsepower is:

$$P/\mathrm{hp} = \frac{[\tau/(\mathrm{ft}\cdot\mathrm{lbf})][\omega/(\mathrm{rev}/\mathrm{min})]}{5252}.$$

Outside the U.S.A. most countries use the newton-meter as the unit of torque. Most automobile specifications worldwide have torques listed in newton-meters. The standard equation relating torque in newton-meters, rotational speed in RPM and horsepower is:

$$P/\mathrm{hp} = \frac{[\tau/(\mathrm{Nm})][\omega/(\mathrm{rev}/\mathrm{min})]}{7124}$$

These are based on Watt's definition of the mechanical horsepower. The constants 5252 and 7124 are rounded; the exact values are 16,500/π and 22,380/π, respectively. See torque.

Drawbar horsepower (dbhp)

Drawbar horsepower is the power a railroad locomotive has available to haul a train or an agricultural tractor to pull an implement. This is a measured figure rather than a calculated one. A special railroad car called a dynamometer car coupled behind the locomotive keeps a continuous record of the drawbar pull exerted, and the speed. From these, the power generated can be calculated. To determine the maximum power available, a controllable load is required; this is normally a second locomotive with its brakes applied, in addition to a static load.

If the drawbar force is measured pounds-force (*F* / lbf) and speed is measured in miles per hour (*v* / (mi / h)), then the drawbar power in horsepower (*P* / hp) is:

$$P/\mathrm{hp} = \frac{[F/\mathrm{lbf}][v/(\mathrm{mi/h})]}{375}.$$

Example: How much drawbar power is needed to pull a cultivator load of 2025 pounds-force through medium soil at 5 miles per hour?

$$P/\mathrm{hp} = \frac{2025 \times 5}{375} = 27.$$

The constant "375" is because 1 hp = 375 lbf·mi/h. If other units are used, the constant is different. When using a coherent system of units, such as SI (watts, newtons, and metres per second), no constant is needed, and the formula becomes $P = Fv$.

RAC horsepower (taxable horsepower)

This measure was instituted by the Royal Automobile Club in Britain and used to denote the power of early 20th century British cars. Many cars took their names from this figure (hence the Austin Seven and Riley Nine), while others had names such as "40/50hp", which indicated the RAC figure followed by the true measured power.

Taxable horsepower does not reflect developed horsepower; rather, it is a calculated figure based on the engine's bore size, number of cylinders, and a (now archaic) presumption of engine efficiency. As new engines were designed with ever-increasing efficiency, it was no longer a useful measure, but was kept in use by UK regulations which used the rating for tax purposes.

$$RACh.p. = D^2 * n/2.5$$

where
D is the diameter (or bore) of the cylinder in inches
n is the number of cylinders

This is equal to the displacement in cubic inches divided by 10π then divided again by the stroke in inches.

Since taxable horsepower was computed based on bore and number of cylinders, not based on actual displacement, it gave rise to engines with 'undersquare' dimensions, i.e. relatively narrow bore, but long stroke; this tended to impose an artificially low limit on rotational speed (rpm), hampering the potential power output and efficiency of the engine. The situation persisted for several generations of four- and six-cylinder British engines: for example, Jaguar's 3.8-litre XK engine had six cylinders with a bore of 87 mm (3.43 inches) and a stroke of 106 mm (4.17 inches), where most American automakers had long since moved to oversquare (wide bore, short stroke) V-8s.

Measurement

The power of an engine may be measured or estimated at several points in the transmission of the power from its generation to its application. A number of names are used for the power developed at various stages in this process, but none is a clear indicator of both the measurement system and definition used.

In general:

Indicated or gross horsepower (theoretical capability of the engine)
minus frictional losses within the engine (bearings, rods, etc), equals
Brake or net horsepower (power delivered directly by the engine)

minus frictional losses in the transmission (bearings, gears, etc.), equals
Shaft horsepower (power delivered to the driveshaft)
minus shaft losses (friction, slip, cavitation, etc), equals
Effective or wheel horsepower

Indicated horsepower (ihp)

Indicated horsepower is the theoretical power of a reciprocating engine assuming that it is completely efficient in converting the energy contained in the expanding gases in the cylinders. It is calculated from the pressures developed in the cylinders, measured by a device called an *engine indicator* - hence indicated horsepower. It was the figure normally used for steam engines in the 19th century but is misleading because the mechanical efficiency of an engine means that the actual power output may only be 70% to 90% of the indicated horsepower.

SAE gross horsepower

Prior to 1972 most American automakers rated their engines in terms of **SAE gross horsepower** (defined under SAE standards J245 and J1995). Gross hp was measured using a blueprinted test engine running on a stand without accessories, mufflers, or emissions control devices. It therefore reflected a maximum, theoretical value, not the power of an installed engine in a street car. Gross horsepower figures were also subject to considerable adjustment by carmakers: the power ratings of mass-market engines were often exaggerated, while those for the highest-performance muscle car engines were frequently underrated.

Brake horsepower (bhp)

Brake horsepower (bhp) is the measure of an engine's horsepower without the loss in power caused by the gearbox, generator, differential, water pump and other auxiliaries. Thus the prefix "brake" refers to where the power is measured: at the engine's output shaft, as on an engine dynamometer. The actual horsepower delivered to the driving wheels is less. An engine would have to be retested to obtain a rating in another system. The term "brake" refers to the use of a band brake to measure torque during the test (which is multiplied by the engine speed in revs/sec and the circumference of the band to give the power).

hp (SAE)

In the United States the term "bhp" fell into disuse after the American Society of Automotive Engineers (SAE) recommended manufacturers use **hp (SAE)** to indicate the net power of the engine, given that particular car's complete engine installation. It measures engine power at the flywheel, not counting drivetrain losses.

Starting in 1971 automakers began to quote power in terms of **SAE net horsepower** (as defined by standard J1349). This reflected the rated power of the engine in as-installed trim, with all accessories and standard intake and exhaust systems. By 1972 U.S. carmakers quoted power exclusively in SAE net hp. The change was meant to 'deflate' power ratings to assuage the auto insurance industry and environmental and safety lobbies, as well as to obfuscate the power losses caused by emissions-control equipment.

SAE net ratings, while more accurate than gross ratings, still represent the engine's power at the flywheel. Contrary to some reports, it does *not* measure power at the drive wheels.

Because SAE gross ratings were applied liberally, at best, there is no precise conversion from gross to net. Comparison of gross and net ratings for unchanged engines show a variance of anywhere from 40 to 150 horsepower. The Chrysler 426 Hemi, for example, in 1971 carried a 425 hp gross rating (often considered to be underrated) and a net rating of 375 hp.

SAE-certified horsepower

In 2005, the Society of Automotive Engineers introduced a new test procedure (J2723) for engine horsepower and torque. The procedure eliminates some of the areas of flexibility in power measurement, and requires an independent observer present when engines are measured. The test is voluntary, but engines completing it can be advertised as "SAE-certified".

Many manufacturers began switching to the new rating immediately, often with surprising results. The rated output of Cadillac's supercharged Northstar V8 jumped from 440 hp (328 kW) to 469 hp (350 kW) under the new tests, while the rating for Toyota's Camry 3.0 L *1MZ-FE* V6 fell from 210 hp (157 kW) to 190 hp (142 kW). The first engine certified under the new program was the 7.0 L LS7 used in the 2006 Chevrolet Corvette Z06. Certified power rose slightly from 500 hp (373 kW) to 505 hp (377 kW).

hp (DIN)

DIN horsepower is the power measured according to the German standard DIN 70020. It is measured at the flywheel, and is in practical terms equivalent to the SAE net figure. However, be aware that DIN "horsepower" is often expressed in metric (Pferdestärke) rather than mechanical horsepower.

hp (ECE)

ECE R24 is another standard for measuring net horsepower. It is quite similar to the DIN 70020 standard, but the requirement for connecting an engine's fan during testing varies. ECE is seen as slightly more liberal than DIN, and ECE figures tend to be slightly higher than DIN. John Deere is one strong adherent to ECE testing.

9768-EC

9768-EC is a standard from the European Union. Generally, ISO-14396 and 9768-EC metrics are very similar.

ISO 14396

ISO 14396 is a new method from the International Standards Organization for all engines not intended for on-road use. Generally, ISO-14396 and 9768-EC metrics are very similar. New Holland is an adherent of ISO-14396 testing.

Shaft horsepower (shp)

Shaft horsepower is the power delivered to the propellor shaft of a ship or turboprop airplane. This may be measured, or estimated from the indicated horsepower given a standard figure for the losses in the transmission (typical figures are around 10%). This metric is uncommon in the automobile industry, through drivetrain losses can be significant.

Effective horsepower (ehp)

Effective horsepower is the power converted to useful work. In the case of a vehicle this is the power actually turned into forward motion.

In automobiles, effective horsepower is often referred to as **wheel horsepower**. Most automotive dynamometers measure wheel horsepower and then apply a conversion factor to calculate net or brake horsepower at the engine. Wheel horsepower will often be 5-15% lower than the bhp ratings because of a loss through the drivetrain.

History of the term "horsepower"

The term "horsepower" was invented by James Watt to help market his improved steam engine. He had previously agreed to take royalties of one third of the savings in coal from the older Newcomen steam engines. This royalty scheme did not work with customers who did not have existing steam engines but used horses instead. Watt determined that a horse could turn a mill wheel 144 times in an hour (or 2.4 times a minute). The wheel was 12 feet in radius, thus in a minute the horse travelled $2.4 \times 2\pi \times 12$ feet. Watt judged that the horse could pull with a force of 180 pounds (just assuming that the measurements of mass were equivalent to measurements of force in pounds-force, which were not well-defined units at the time). So:

$$power = \frac{work}{time} = \frac{force \times distance}{time} = \frac{(180\ \mathrm{lbf})(2.4 \times 2\pi \times 12\ \mathrm{ft})}{1\ \mathrm{min}} = 32,572$$

This was rounded to an even 33,000 ft·lbf/min.

Others recount that Watt determined that a pony could lift an average 220 pounds 100 feet (30 m) per minute over a four-hour working shift. Watt then judged a horse was 50% more powerful than a pony and thus arrived at the 33,000 ft·lbf/min figure.

Engineering in History recounts that John Smeaton initially estimated that a horse could produce 22,916 foot-pounds per minute. John Desaguliers increased that to 27,500 foot-pounds per minute. "Watt found by experiment in 1782 that a 'brewery horse' was able to produce 32,400 foot-pounds per minute". James Watt and Matthew Boulton standardized that figure at 33,000 the next year.

Put into perspective, a healthy human can produce about 1.2hp briefly (see Orders of magnitude (power)) and sustain about 0.1hp indefinitely, and trained athletes can manage up to about 0.3 horsepower for a period of several hours.

Most observers familiar with horses and their capabilities estimate that Watt was either a bit optimistic or intended to underpromise and overdeliver; few horses can maintain that effort for long. Regardless, comparison to a horse proved to be an enduring marketing tool.

Horsepower from a horse

R. D. Stevenson and R. J. Wasserzug published an article in Nature 364, 195-195 (15 Jul 1993) calculating the upper limit to an animal's power output. The peak power over a few seconds has been measured to be as high as 14.9 Hp. However, for longer periods an average horse produces less than one horsepower.

Conversion of historical definition to watts

The historical value of 33,000 ft·lbf/min may be converted to the SI unit of watts by using the following conversion of units factors:

- 1 ft = 0.3048m
- 1 lbf = g_n × 1 lb = 9.80665 m/s^2 × 1 lb × 0.45359237 kg/lb = 4.44822 kg·m/s^2 = 4.44822 N
- 60 seconds = 1 minute

$$33,000\frac{\mathrm{ft}\cdot\mathrm{lbf}}{\mathrm{min}} \times \frac{0.3048\ \mathrm{m}}{\mathrm{ft}} \times \frac{4.44822\ \mathrm{N}}{\mathrm{lbf}} \times \frac{\mathrm{min}}{60\ \mathrm{s}} = 745.69987158227022\ \frac{\mathrm{N}\cdot\mathrm{m}}{\mathrm{s}}$$

And the watt is defined as $1\ \mathrm{W} = 1\frac{\mathrm{N}\cdot\mathrm{m}}{\mathrm{s}}$ so the historical figure of 33,000 ft·lbf/min converts exactly to the modern definition.

Switcher

An EMD SD39 and slug in switching service.

A **switcher** or **shunter** (Great Britain: **shunter**; USA: **switcher**, except Pennsylvania Railroad: **shifter**) is a small railroad locomotive intended not for moving trains over long distances but rather for assembling trains ready for a road locomotive to take over, disassembling a train that has been brought in, and generally moving railroad cars around - a process usually known as switching (UK: shunting). They do this in classification yards. Switchers may also make short transfer runs and even be the only motive power on branch lines.

Light electric shunter SBB Tem 346

A modern US switcher, an EMD MP15DC.

The typical switcher is optimised for its job, being relatively low-powered but with a high starting tractive effort for getting heavy cars rolling quickly. Switchers are geared to produce high torque but are restricted to low top speeds and have small diameter driving wheels . Slugs are often used because they allow even greater tractive effort to be applied. Nearly all slugs used for switching are of the low hood, cabless variety. Good visibility in both directions is critical, because a switcher may be running in either direction; there's no time or space to turn a locomotive in a switcher's job. Steam switchers are either tank locomotives or have special (smaller) tenders, with narrow coal bunkers and/or sloped tender decks to increase rearward visibility. Headlights, where carried, were mounted on both ends. Diesel switchers tend to have a high cab and often lower and/or narrower hoods (bonnets) containing the diesel engines, for all round visibility. Now, the vast majority of switchers are diesels, but countries with near-total electrification, like Switzerland, use electric switchers.

Switching is hard work, and heavily used switch engines wear out quickly from the abuse of constant hard contacts with cars and frequent starting and stopping.

British and European locomotives of this type tend to be much smaller than the common size in the United States.

Diesel-electric

A number of vehicles use a **diesel-electric** powerplant for providing locomotion. A diesel-electric powerplant includes a diesel engine connected to an electrical generator, creating electricity that powers electric traction motors.

This kind of power transmission is used by locomotives (see that article for details), used for pulling or pushing trains. Diesel-electric powerplants have also been used in submarines and surface ships and some land vehicles. Vehicles using diesel-electric power system can be considered as a class of hybrid electric vehicle, especially, if the electric energy is also coming from rechargeable batteries.

Submarines

When the diesel engine was first installed in submarines before the First World War, it revolutionized submarine tactics because its range (or operating time) far surpassed that of the gasoline engine, and leaked vapors of its fuel were far less prone to explode within a submarine cabin. The fuel was also easier to stow. In submarines, the engine is connected to generators to produce electric energy that is stored in batteries for running underwater where oxygen is not available to feed the engines. It had been standard for them to use a driveshaft directly connecting the diesel engine, generator and propellers.

There were a variety of clutch mechanisms for various connections as well. However, the long driveshaft has often been a source of trouble, also producing noise and vibration.

Some Soviet submarines had three propellers, and could be used in a variety of ways: each running on its diesel engine; either the central one or the outer two could each be connected to a diesel engine with or without the other propeller running on electric; or the engines could via snorkel be recharging the batteries while the central propeller was quietly running on its electric motor; or all three could be running on electric motors.

The diesel engine performance was critical for a conventional submarine's success. Navies imported and copied successful designs. The Germans had some excellent diesel designs for their U-boats, but they also had some designs which were not so good. The Americans had a similar history; their last diesel engine design was radial in form, its driveshaft axis angled vertically. These designs were subsequently abandoned. Older submarines had to be cut in half through the engine room and proven engines installed in a lengthened hull section to replace the unreliable but space-efficient designed engine. Since the correction, European submarine diesels have shown advances.

Modern diesel-electric submarines don't have a direct connection of the diesel engine to the propeller anymore: The usually single propeller is driven directly by an electric motor. Two or more diesel-generators provide electric energy for loading the batteries and/or driving the electric motor. This mechanically insulates the noisy engine compartement from the outer pressure hull and reduces the acoustic signature of the submarine. Even some nuclear submarines decouple their reactor room this way, e.g. all French classes, like the Rubis and Redoutable and the Chinese Type 093 class, have turbo-electric propulsion.

Ships

Siemens Schottel azimuth thrusters

Even though diesel-powered motor ships have been in use since 1912 (e.g. with the Selandia) and steam-turbine/electric propulsion at least since the 1920s (Tennessee class battleships), the practice of using diesel-electric powerplants in surface ships has been a more recent development. The Finnish "coastal battleship " *Ilmarinen*, laid down in 1929, was among the first surface ships to use diesel-electric transmission. Later the technology was used in diesel powered icebreakers.

Some modern ships, including cruise ships and icebreakers, use electric motors in pods called azimuth thrusters underneath to allow for 360° rotation, meaning that the ships are far more maneuverable.

Some vehicles also use gas turbines in the same way. In fact, some use a combination: the *Queen Mary 2* has a set of diesel engines in the bottom of the ship plus a gas turbine near the top exhaust tower. All are used for generating electrical power, and none of the ship's propellers are directly connected to any engines.

Tugboats

One example of a successful conversion from steam to diesel electric was in the AT&SF tugboat*Hastings', operated on San Francisco Bay to move barges of railroad cars in a side-towing arrangement between specialized barge slips The* Hastings *was originally built as a wartime ocean going rescue tugboat using water tube boilers and a unaflow steam engine, and a similar powerplant was used in the postwar* Engle' which still retains the Unaflow steam engine today. Conventional diesel engines were unsuitable for this application, owing to the time that it took to reverse the engine and produce power, while a steam engine had the responsiveness to bring the barge safely into the slip (even though operated through an engine room telegraph to an operator). The engine room crew consisted of one engineer and two firemen, a substantial proportion of the total crew of eight. By replacing the steam engine with a diesel electric unit (with parts commonality with a locomotive), maintenance was both simplified and reduced, several crew members could be eliminated, and the responsiveness to throttle operation (now directly controlled from the bridge) was substantially improved.

Locomotives

The Pioneer Zephyr used a diesel-electric drivetrain

In the 1920s, diesel-electric technology first saw limited use in switchers (or *shunters*), locomotives used for moving trains around in railroad yards and assembling and disassembling them. One of the first companies to offer "Oil-Electric" locomotives was the American Locomotive Company. The ALCO HH series of diesel-electric switcher entered series production in 1931. In the 1930s, the system was adapted for streamliners, the fastest trains of their day. Diesel-electric powerplants became popular because they greatly simplified the way motive power was transmitted to the wheels and because they were both more efficient and had greatly reduced maintenance requirements. Direct-drive transmissions can become very complex, considering that a typical locomotive has four or more axles. Additionally, a direct-drive diesel locomotive would require an impractical number of gears to keep the engine within its powerband; coupling the diesel to a generator eliminates this problem. Some attempts were made at using hydraulic fluid as a transmission medium, and it proved to be somewhat more efficient than diesel-electric technology. However, the complexity of both the direct-drive and hydraulic systems meant that breakdowns were more common.

Other land vehicles

The diesel-electric powerd Liebherr T282 dumper

Diesel-electric propulsion was tried on some military vehicles, such as tanks. One example was the ill-fated Maus tank. Currently no tank uses this principle for movement, but it's quite common to train the turret and/or guns with electric motors powered by diesel or turbine APUs.

More success had diesel-electric propulsion on the civilian market: Big mining machines like the Liebherr T282B dump truck or LeTourneau L-2350 wheel loader are powered that way. Also NASA's huge Crawler-Transporters are propelled diesel-electrically.

The U.S. military is considering a replacement for its HMMWV utility vehicle which would use a diesel-electric propulsion system. Such a vehicle could operate its electrical systems for an extended period without running the engine, due to the large battery reserves. When stealth is desired, it could drive using only electrical power for a limited time.

How to Become a Diesel Mechanic

Did you take apart your mom's toaster and try to fix it when you were a kid? What about the TV, the computer, the radio, the car? If you love the technical aspect behind these tasks but don't want to be tied to a desk all day, a career as a diesel mechanic may be perfect for you.

Instructions

- **STEP 1:** Take your Lego skills to shop and mechanics classes in high school, as well as algebra, geometry, physics and English. Extracurricular activities that provide mechanical experience and computer literacy would also be beneficial for those looking to become diesel mechanics.
- **STEP 2:** Know the difference between auto and diesel mechanics. Not only do they work on different equipment, but systems operate differently in some cases.
- **STEP 3:** Volunteer or work part-time on a nearby farm if that option is available to you. Often, you can get hands-on experience tearing down tractors or machinery and learning how everything works.
- **STEP 4:** Take an interest in a car or truck someone you know is restoring. This is a perfect way to get your hands dirty and decide if you are interested enough in mechanics to pursue it as a career.
- **STEP 5:** Set aside a few days to observe a diesel mechanic at work. This possible mentor may be able to give you some practical tips and send you in the direction of a good diesel mechanics program.
- **STEP 6:** Look for a diesel mechanics program that offers the training you want. Most community, career and technical colleges - and some colleges and universities - offer a one to two-year associate's degree or diploma program that allows students to specialize in different areas of diesel mechanics, including heavy equipment (construction), agricultural equipment and tractor-trailers.
- **STEP 7:** Consider getting a job with a large company that offers on-the-job training right out of high school. Some large companies will even foot the entire bill of getting a diesel mechanic trained and certified.

- **STEP 8:** Prepare yourself for the trade's technical aspect, especially the need for some fairly advanced mathematics and computer skills. Many systems on large diesel vehicles and equipment are electronic, so students must be able to disassemble, diagnose, fix and reassemble these systems, too.
- **STEP 9:** Put in at least two years of practical work experience after graduating before taking the Automotive Service Excellence (ASE) exams to become certified. After certification, the technician title will entitle you to slightly higher pay.

How to Buy Mechanic Tool

Are you wondering where you can buy cheap mechanic tool, high quality mechanic tool or free mechanic tool? Well we probably can't help you find it for free.

Related Ads:

- Wrench
- Hydraulic Torque Wrench
- Titanium Tool
- Allen Wrench Sets
- Hydraulic Tool
- Car Tool Kits
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Picture	Product	Price
	T X BMW R1150R R1150RT R1150GS R1200cl R1200gs	$14.60
	T0RX BMW 325i 728i 316i 735i 730i 315i 520i M3 x 5 745i	$9.38

	MUSTANG 2 STREET ROD BIG DISC BRAKE KIT SLOTTED ROTORS	$239.00
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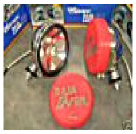
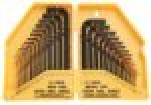
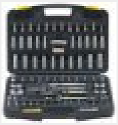
	TR2 REPAIR SERVICE & Frame MANUAL Triumph TR-2 MANUALS	$19.99
	MGB PARTS MANUAL plus MG PART & SERVICE MANUALS	$22.00
	DICK CEPEK 130W BAJA 6" STAINLESS OFF ROAD LIGHTS -PAIR	$56.00
	SBF FORD 260-289-302W V8 PAINTED OIL PAN MUSTANG GALAXY	$24.95
	PONTIAC SHORT OEM STYLE CHROME VALVE COVERS GTO	$17.00

11" CHROME BOOSTER KIT 1976 77 78 79 80 81 CHEVY CAMARO

$220.00

Photo	Product	Price
	FULLER 130-8030 30-Piece Combo SAE/Metric Hex Key Set	$11.80
	Apollo Precision Tools DT9706 - 39 Piece General Tool Set	Too low to display
	Stanley 89-806 151-Piece Professional Grade Mechanic's Tool Set	$149.00
	Stanley 89-804 96-Piece Professional Grade Mechanics Tool Set	$67.00
	Allied 59091 235-Piece Mechanic's Tool Set in Fold Out Case	$49.99
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